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Industrial Decarbonization and the Role of Natural Gas

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Executive Summary

Historically, the cost and availability of resources have driven energy transitions. These transitions have tended to be evolutionary in other words gradual, and ongoing. The current clean energy transition, on the other hand, is largely driven by environmental concerns and climate change--widespread mid-century goals for deep decarbonization are shaping policies, guiding investments, supporting innovation, and building infrastructure for an energy transition that now has a twenty-five-year time horizon.

In this context, industrial decarbonization raises issues about the availability of technologies, affordability, competitiveness, and national and regional policies that could impact the pace of change. The industrial sector is currently responsible for nearly one-quarter of global carbon emissions.[1,1] In 2022, three industrial subsectors alone -- chemicals, steel and iron, and cement industries were responsible for around 55% of industrial emissions. Moreover, heavy industries (chemical, steel, cement) are likely to remain the leading sources of CO_2 emissions in the future.[2] Industrial processes also use carbon intensive fossil fuels as feedstock for products such as plastics. In the US manufacturing sector, including chemicals, petroleum and coal products, paper, primary metals, food, nonmetallic minerals, and all other fossil fuels for heat and electricity is around 68% of energy use, and 32% is for feedstocks.[3]

Transitioning to cleaner energy sources is highly complex in the energy-intensive industrial sector, which requires high heat for various processes; this heat is, by and large, generated by fossil fuels, including natural gas. At the same time, alternatives for achieving the highest required temperatures for key industrial processes are not available commercially at scale or are in the very early stages of development. In the EU-28 in 2019, fossil fuels were roughly 77% of the energy carriers used in the industrial sector; natural gas comprised around half of fossil fuel use by the EU's industrial sector, and coal was roughly 28%.[4]

As long as industry, in the United States and globally, is highly reliant on fossil fuels, and many new technologies for decarbonization of industrial emissions aren't in commercial use or are in a limited scale, industrial decarbonization will require innovation, planning, investment, policy support, and global cooperation. The industrial sector employs many people and is significant to many local, national, and regional economies. Decarbonization of the industrial sector will necessarily include a focus on jobs and affordability of the products produced and thus may be a lower priority than economic development for emerging economies. Also, many of the building blocks needed for a clean energy future currently rely on energy intensive (i.e., made from fossil fuels) industrial products. Wind

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[1] Including process emissions but not including indirect emissions from electricity used for industrial processes.

turbine support towers, for example, are made from aluminum, steel, and copper, and nacelles are largely made from steel and fiberglass.

Regarding the highest emitting industrial processes, both costs and technical constraints need the focus of policymakers and the investment community to help reduce emissions of decarbonize some of the most difficult to decarbonize subsectors in the economy. Affordability of new technologies and alternative fuel sources will also be a critical driver of decarbonization of the industrial sector. The industrial sector is likely to evolve, with a focus on reducing emissions during the transition, supporting increased efficiency and the use of renewable energy to achieve near-term reductions of a significant percentage of industrial carbon emissions and contributing to a more sustainable energy mix. However, the pace and direction of this evolution will vary by region depending on local resources, policies that balance emissions reductions and economic development, technologies, and market conditions.

Globally, nations have three basic energy needs that vary by country and region: security, reliability, and affordability. The ongoing European energy crisis – the result of Russia's invasion of Ukraine in early 2022 – has impacted the affordability and reliability of natural gas, including liquefied natural gas (LNG) globally. As a result, the solutions to industrial decarbonization will need to be pragmatic, in some instances sequenced, and consider the local or regional energy mix.

The ongoing consumption of natural gas in the industrial sector – both in volume and over time – will depend on how effectively its uses can be adapted to changing energy and industrial landscapes, and how associated greenhouse gas (GHG) emissions are mitigated and aligned with global, regional, and national climate objectives. At a high level, this analysis examines industrial decarbonization, focusing on greenhouse gas emissions from energy-intensive industries, and the potential of natural gas as a facilitator of the clean energy transition, and energy market evolution, as well as long-term solutions for reducing carbon emissions in high-heat industrial applications.

This analysis specifically focuses on the role of natural gas in the industrial sector, what options could replace natural gas in the industrial sector, where there are no current technology options for replacing natural gas as both a high-heat source and feedstock in key industrial subsectors, and how these processes might be decarbonized in the near to mid-term. This analysis will inform EFI Foundation's Global Gas Phase II study, which is looking at natural gas in the context of deep decarbonization with specific analyses of Europe and Asia.

Key Findings

- Investments are needed to address numerous opportunities to accelerate industrial decarbonization (i.e., Carbon Capture Utilization and Storage (CCUS), low-carbon fuels, industrial electrification, and increasing energy efficiency).
- Achieving net-zero CO_2 emissions in the top CO_2-emitting industrial subsectors by 2050 will require the application of multiple decarbonization technologies and approaches in parallel. Coal-to-gas and fuel switching are immediate solutions to decarbonize the industry, but economics will drive this transition and solutions are region-specific as they are dependent on costs, investments, and the price of natural gas.
- Lower temperature (<300^{o}C) process heat in chemicals, food, and refining suggests there could be early opportunities for potentially zero and low-carbon energy sources such as electricity from zero-carbon generation sources that can supply heat in this range. Technical challenges remain for higher heat processes (above 600^o C) in "hard-to-abate" industrial sectors.
- The first drivers of decarbonization efforts can be driven by policy-based initiatives, such as promoting decarbonization through incentives, direct investments, and tax credits such as the promotion of CCUS via 45Q tax credits in the United States or other initiatives.
- Decarbonization policies and regulations in developed nations present a risk of segmenting global markets, with cleaner products primarily directed towards OECD countries, while emissions-intensive production exists or moves to Emerging markets.
- The reduction in Russian gas deliveries to Europe has increased investment in alternative supply sources, including coal, and the expansion of LNG infrastructure. This could be an early signal of global shifts in natural gas production and distribution systems.

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1. Introduction

This report examines the opportunities, challenges, and evolving dynamics surrounding the role of natural gas in global efforts to decarbonize the industrial sector. Through a comprehensive review of current industry practices, research trends, and case studies this paper seeks to provide an informed perspective on the role of natural gas in industrial decarbonization. The analysis is structured in four sections:

- An overview of the role of natural gas in the industrial sector and emissions profile in addressing questions related to market evolution and adaptation; the impact of decarbonization on competitiveness, rate of production and industrial demand.
- The call to action for industrial decarbonization and the importance of addressing it through decarbonization policies, regulations, and how industries are switching to natural gas and other low-carbon alternatives considering Paris and net-zero commitments.
- A detailed review of industrial decarbonization technologies with a focus on how industries are switching to low-carbon alternatives.
- Two case studies of the role of natural gas in industrial decarbonization.

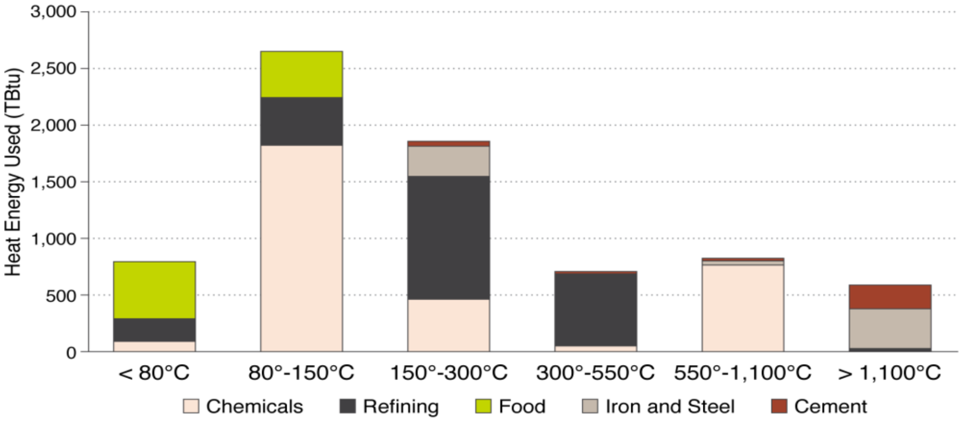
The following sections will discuss the drivers for decarbonizing the industrial sector, the role of natural gas in the industrial sector, policy, and technology options for industrial decarbonization, and policy recommendations for accelerating industrial decarbonization.

1.1. Energy Requirements of the Industrial Sector

The industrial sector is responsible for almost a quarter of all CO2 emissions and is a major energy consumer. According to the EIA, “The industrial sector consists of all facilities and equipment used for producing, processing, or assembling goods. The industrial sector includes manufacturing, agriculture (farming), construction, fishing, forestry, and mining (which includes oil and natural gas extraction) ...Industry uses fossil fuels and renewable energy sources for: heat in industrial processes and space heating in buildings, boiler fuel to generate steam or hot water for process heating and generating electricity; … [and as] feedstocks (raw materials) to make products such as plastics and chemicals.”[5]

There are different types of industrial heat demand. The use of lower-temperature process heat, typically below 300℃, is widespread in subsectors like chemicals, food production, and refining (Figure 1). This prevalence of lower-temperature process heat highlights the potential for low carbon or carbon-free technologies capable of providing heat in this temperature range, including electricity generated by renewable energy sources and heat pumps. Temperature ranges between 300-500 ℃ are mainly used for refining; temperatures above 550℃ are used in energy and heat intensive industries like iron, steel, glass, cement, and chemicals.

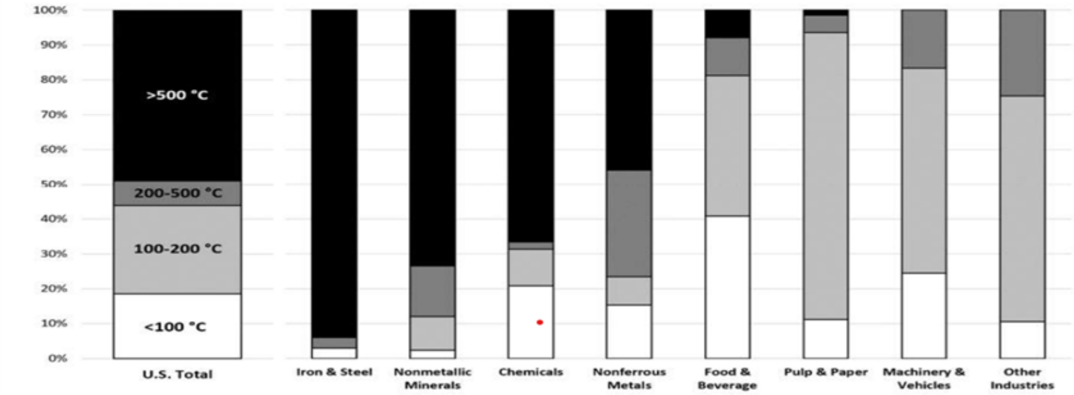
Figure 1: Distribution of process heat temperature ranges by US industrial subsector, 2014



Source: Hasanbeigi, A., Kirshbaum, L. A., Collison, B., & Gardiner, D. (2021). Electrifying U.S. Industry. Renewable Thermal Collaborative, 21-1.

Translating these volumes into percentages underscores the importance of the high heat needs of critical U.S. (and global) industries. As seen in Figure 2, around 50% of overall heat demand for these industries is over 500° C. For iron and steel, it is around 93%, non-metallic industries around 75%, chemicals around 68% and nonferrous metals, e.g., aluminum, around 45%.

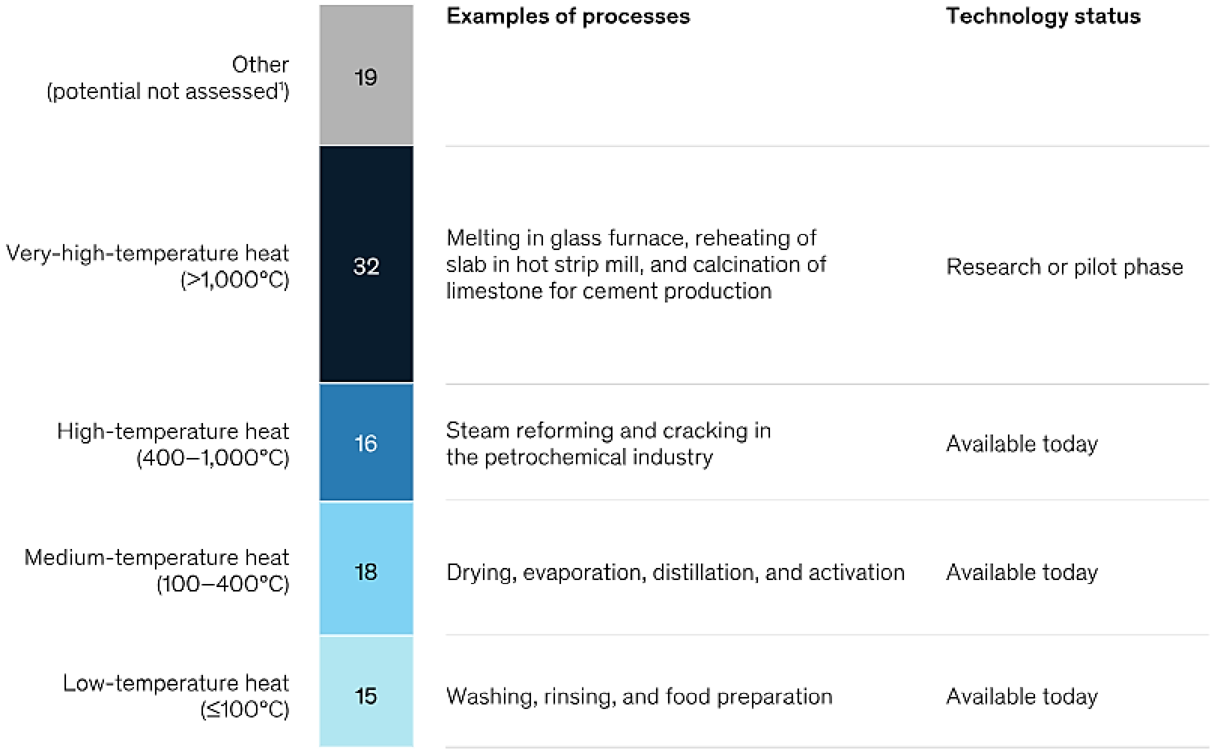
Figure 2. Percentage Heat Demand by Temperature Range in Industry (U.S. 2021) *



*Source: Decarbonizing Low-Temperature Industrial Heat in the U.S., October 2022, Jeffrey Rissman, Energy Innovation Policy and Technology LLC. * Nonmetallic minerals include cement, lime, brick, glass, tile, etc.*

Understanding the heat requirements for a range of key and cross-cutting industrial processes where gas plays a significant role is also important for developing decarbonization pathways for industry. Figure 3 shows percentages of temperatures needed for many of these processes. The analysis accompanying this figure concluded that 50% of these processes could be electrified with today's technologies. The figure also shows that approximately 32% of fuel consumption for energy is for processes that require very high temperatures and electrification technology is still in research or pilot phases. These processes require a fuel such as natural gas to achieve the levels of heat needed.

Figure 3. Percentage Share of Heat Requirements for Key/Cross-cutting Industrial Processes



		Examples of processes	Technology status
Other (potential not assessed[1])	19		
Very-high-temperature heat (>1,000°C)	32	Melting in glass furnace, reheating of slab in hot strip mill, and calcination of limestone for cement production	Research or pilot phase
High-temperature heat (400–1,000°C)	16	Steam reforming and cracking in the petrochemical industry	Available today
Medium-temperature heat (100–400°C)	18	Drying, evaporation, distillation, and activation	Available today
Low-temperature heat (≤100°C)	15	Washing, rinsing, and food preparation	Available today

Note: Current electricity consumption and energy consumption as feedstock are excluded. Sectors included are chemicals and petrochemicals, iron and steel, nonmetallic minerals, nonferrous metals, food and tobacco, transport equipment, machinery, textile and leather, wood and wood products, paper pulp and print, mining, industrial feedstock, and other industrial nonenergy use. Industrial energy consumption for which the source data do not specify a sector (nonspecified industrial energy consumption) is attributed to other industrial sectors and uses.

[1] Includes heating, ventilation, and air-conditioning; transportation; and refrigeration.

Source: Expert interviews; *Heat and cooling demand and market perspective*, JRC Scientific and Policy Reports, European Commission, 2012, publications.jrc.ec.europa.eu; "Manufacturing energy and carbon footprints (2014 MECS)," US Office of Energy Efficiency & Renewable energy, September 2018, energy.gov; *World energy balances 2019*, IEA, September 2019, iea.org; McKinsey analysis

Source: McKinsey et. al.

The electrification of the remaining 68% is technically possible but has not yet been proven commercially viable nor is it required by regulation. This category encompasses the manufacturing of new steel, cement, glass, and ceramics. Various technologies are under development to electrify these processes but are not yet mature.[6]

In the United States, process heat is the largest energy consumer in manufacturing, accounting for 51% of total on-site manufacturing energy consumption in 2018, with a corresponding 31% share of energy-related greenhouse gas emissions in the manufacturing sector.[7] Approximately 30% of process heat demand requires 150°C or lower, making it suitable for electrification or the use of other low- or zero-emission heat sources, including heat pumps, microwave systems, infrared technologies, and environmentally friendly options like solar thermal and nuclear power. Notably, advanced gas-cooled very high-temperature reactors (VHTR) are emerging as an option, capable of reaching temperatures as high as 900°C, suitable for distributed applications.

A McKinsey report about decarbonization of industry in the Netherlands, concludes that about 60% of industrial processes can be electrified by 2040 and 80% by 2050, with an investment of approximately €23 to 71 billion in the Netherlands alone.[8] Electric alternatives for conventional equipment are readily accessible for heat demands of roughly up to 40°C. While electric furnaces for industrial heat requirements reaching up to approximately 1,000°C are technically feasible, they have not yet achieved widespread commercial availability for all applications. A notable restriction is that while feasible these new technologies may not be ready for large scale industrial manufacturing needs.

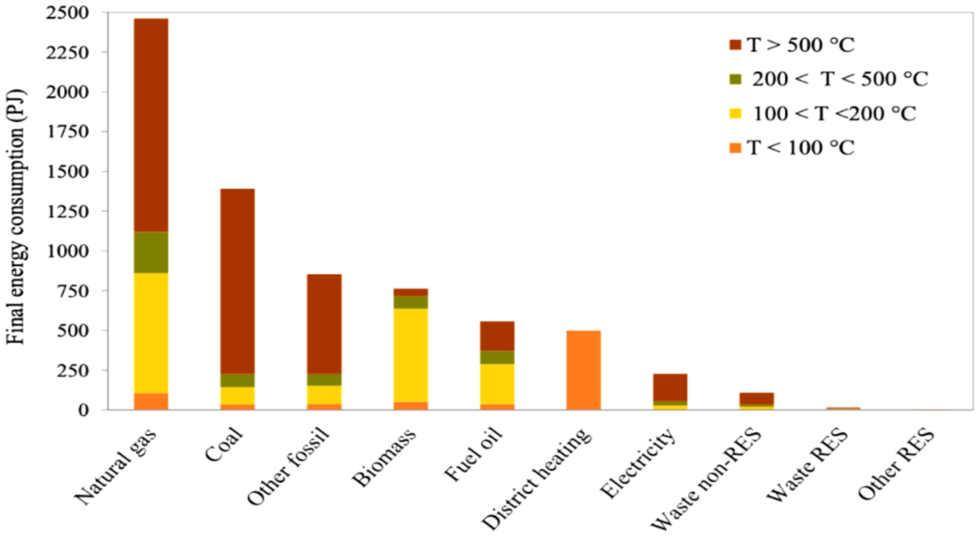
1.2. Natural Gas Uses in Industrial Processes and Manufacturing

In the U.S. industrial sector, natural gas plays a crucial role, supplying nearly one-third of the energy consumed by the sector. It serves various purposes, including on-site electricity generation for powering boilers and furnaces. and turbines, providing process heat for tasks like glass melting, food processing, metal preheating, and product drying, and supporting combined heat and power (CHP) systems. Figure 4 shows the final volumes of energy consumption for industrial heat by source and volumes associated with the temperatures needed for key industrial processes in the EU-28.

As seen in the figure, natural gas plays the most significant role in all temperature ranges but especially in temperatures greater than 500 °C. Coal, a very close second to natural gas, combined with “other fossil”, and fuel oil, however, substantially exceed volumes of natural gas used by the EU’s industry for high heat processes. Depending on costs and other infrastructure issues, changing carriers for high heat process to natural gas could provide an option for reducing emissions from the industrial sector; this option is discussed later in this analysis.

Another issue is that approximately 70% of ammonia used in fertilizers is produced via natural gas-based steam reforming, while most of the remainder if coal gasification making natural gas a critical enabler of food security across the globe. Ammonia production, utilizing 20% (coal is 5% of total coal demand) of industrial natural gas demand, is more emissions intense than steel and cement industries combined.[9] Natural gas is also a raw material input, serving as a feedstock in the production of chemicals, and plastics.[10,11] Other uses include heating, cooling, and water heating in residential, commercial, and industrial buildings.[12] A relatively small amount of natural gas is consumed in the transportation sector, where it is used primarily as compressed natural gas (CNG) and LNG in public transportation and fleet operations.

Figure 4. Energy carriers used for industrial heat in the EU-28, categorized by temperature levels, 2020



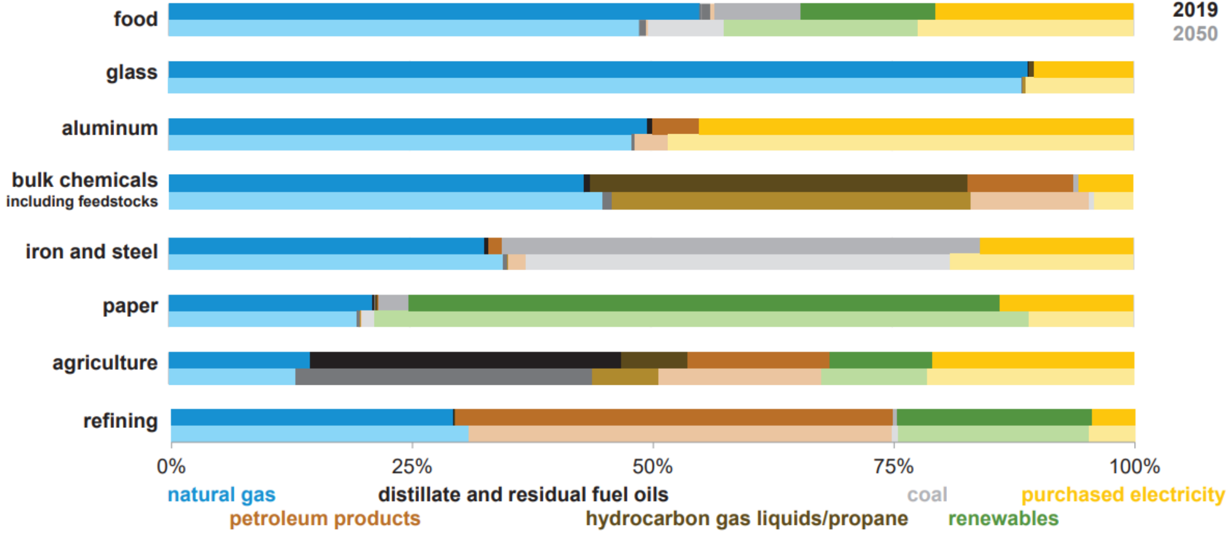
Source: Decarbonizing industrial process heat: the role of biomass. Ollie Olson & Fabian Schipfer, IEA Bioenergy Task 40, December 2021

As seen in Figure 4, a significant amount of natural gas is used as an industrial heat source. It can be used, for example, to provide the heat needed for industrial furnaces and kilns. Burning natural gas can allow very high temperatures that are necessary to manufacture steel, cement, glass, and some chemical manufacturing processes.[13] It is commonly used in industrial furnaces because it provides efficient and precise temperature control. These furnaces are used in metal smelting, glass production and ceramic manufacturing.[14] A summary of principal natural gas industrial usage by category of use (fuel, furnaces, feedstocks, steam) includes:

- ***Furnaces***:
  - Metal smelting
  - Glass production (including for silicon chips)
  - Ceramic manufacturing
- ***Steam generation*:**
  - Power generation
  - Heating
  - Sterilization
- ***Feedstocks (SMR)*:**
  - Ammonia
  - Methanol
  - Hydrogen
  - Carbon Fiber
- ***Fuel*:**
  - Cement, brick, and blocs kilns

Other industrial subsectors that use natural gas include waste treatment, petrochemicals, mining and smelting, metal processing, food processing, and textiles. Figure 5 shows natural gas use by various industries as an approximate percentage of total energy consumption. It should be noted that electricity is its own category in this figure, in addition to the range of fuel sources depicted in the graph. In 2021, natural gas generated 39% of U.S. power, this would add to the percentage of natural gas used for the key industrial subsectors depicted in the figure. Thus, through increased electrification, a portion of the carbon footprint could shift from industrial processing to the power sector dependent on the source of fuel.

Figure 5. Energy Consumption by Fuel Varies Across Energy-Intensive Industries, Approximate Percentage of Natural Gas (EIA AEO2020 Reference Case)



Source: US EIA, 2020 AEO

The chemical industry offers a good example of industrial energy consumption, including natural gas. It is also the third largest CO_2 emitter in the industrial sector. About half of the energy consumption by the chemical industry – including natural gas -- is as a feedstock (Figure 6).[15] Natural gas is also used to generate power, high-temperature steam, and heat, which are essential for many chemical processes, including distillation, evaporation, and reaction heating. In the EU in 2021, the chemical and petrochemical industries were the most significant industrial energy consumers. consumer of natural gas.   This reliance includes:

1. The manufacturing of chemicals and chemicals products, for which natural gas was 35.0% of final energy consumption; and
2. The manufacturing of primary pharmaceutical products and pharmaceutical preparation. While a much smaller energy consumer compared to chemicals and chemical products, natural gas was 48% of its total energy consumption.

In both subsectors, electricity represented the second highest percentage of energy use. The REPowerEU[b] plan identifies the chemical industry as a subsector where there could be a significant opportunity for reductions in natural gas consumption and the associated emissions with appropriate policies and technologies.[16]

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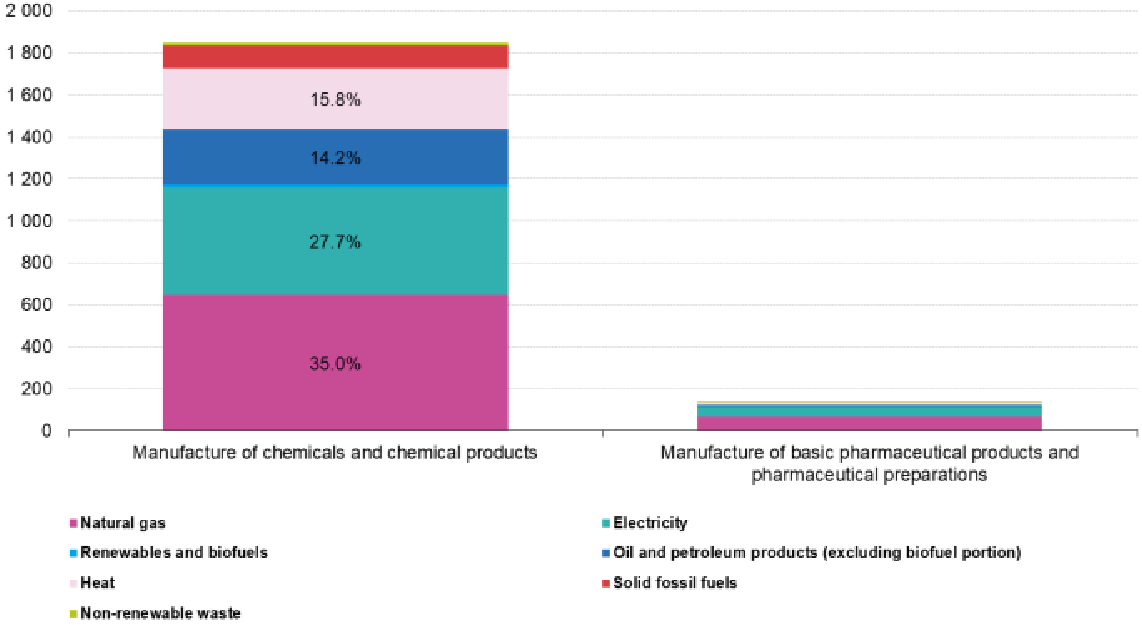
[b] **REPowerEU** is an EU plan that aims to rapidly reduce EU dependence on Russian fossil fuels by fast forwarding the clean transition and joining forces to achieve a more resilient energy system.

Figure 6. Total final energy consumption in the chemical and petrochemical industries, EU, 2021 (PJ)



Source: Eurostat, Statistics explained, Final energy consumption in industry – detailed statistics, 2023

Additional analyses conclude that the chemical sector will comprise nearly one-fourth of gas-demand growth until 2035. According to the report, along with other industrial sectors, chemicals will account for approximately 50% of the growth in natural gas demand, as natural gas is a primary feedstock to produce a wide range of chemicals, including ammonia, methanol, and hydrogen. These chemicals are used as essential raw materials in the production of a wide range of other chemical products.[17] Examples include:

- Ammonia, which serves as a crucial ingredient in the production of ammonium nitrate for fertilizers, ammonium sulfate for agricultural applications, and urea for use in both fertilizers and plastics manufacturing.
- Methanol, which plays a vital role in the creation of formaldehyde for resins and adhesives and acetic acid for textiles and plastics.
- Hydrogen, a product that is indispensable for producing hydrochloric acid for the manufacturing of PVC (polyvinyl chloride), hydrogen peroxide for bleaching in the pulp and paper industry, and ammonia synthesis, which is a key step in fertilizer production.

As noted, ammonia -- a key ingredient in fertilizers -- is made, in part, from natural gas. It is produced, through a process called steam methane reforming (SMR) that can be used to produce hydrogen, which is used for fuel cells, refining, and other industries.[18]

Natural gas is also used to make carbon fiber. Carbon fiber composites are lightweight, strong materials, whose mechanical properties make them an ideal substitute for heavier steels currently used in many applications. For example, according to a study, replacing steel in automotive with carbon fiber composites can significantly improve the vehicle's fuel economy.[19] Carbon fiber is also used in critical sectors such as aerospace and defense, as well as in the wind energy industry, where it is an essential component of turbine blades.

The carbon contained in natural gas is used as a feedstock in a four-stage system to produce carbon fiber. Methane is first decomposed into hydrogen and carbon and combined into a carbon/metal aggregate. Second, the carbon/metal aggregate is melted, producing a liquid melt containing dissolved carbon. Third, the melt is solidified into a homogeneous ribbon. Fourth, carbon is extracted from the ribbon in the form of fiber or fiber precursor. Finally, the metal content of the ribbon is reclaimed and recycled back to the start of the process for further methane decomposition. Temperatures needed for this process are as high as 2800°C.[20]

1.3. The Value of Gas-Intensive Industries to the U.S. Economy

The range of industries that use significant amounts of natural gas for heat, as a feedstock, or for power generation have significant value to the global and U.S. economies. They are also essential industries for economic development in the developing world. Affordability will be a key consideration to ensure uptake and deployment in the least developed world and to compete in export markets.

In 2022, examples of the economic value of and jobs associated with key U.S. industrial subsectors supported by natural gas include:[21]

- **Glass and glass products:** $20.5 bn, employs approximately 82,000 people.
- **Iron, Steel, and Steel products:** $99.1 bn, employs approximately 136,000 people.
- **Aluminum: $**32.4 bn, employs approximately 60, 200 people.
- **Plastics:** $200.8 bn, employs approximately 618,800 people.
- **Chemicals:** $707.8 bn, employs approximately 905,500 people.
- **Agricultural chemicals:** $31.9 bn, employs 36,900 people.

Collectively these sectors represent approximately $1.09 trillion in value to the U.S. economy and around 1.8 million U.S. jobs. Again, these data underscore the critical role that natural gas plays in the industrial sector and the overall economy. This highlights critical drivers and needs such as preserving industrial competitiveness, jobs and affordability while meeting the need for deep decarbonization of energy systems.

Box 1

The importance of the industrial sector to the clean energy transition

The industrial sector – and natural gas by virtue of its significant uses by the sector – also supports the deployment of renewable energy through the manufacture of key technologies, including wind turbines and solar arrays. Industry, supported in part by natural gas, produces the steel, carbon fiber, concrete, and glass needed for these and other key renewable technologies.

1.4. Fossil Energy/Natural Gas Demand Forecasts

The EIA reference case shows an increase in fossil energy demand through 2050. EIA projections for global coal consumption in 2050 compared to 2022 actuals show a 4.1% overall increase (2022/8465m short tons compared to 2050/8813. For liquid fuels, EIA projections show a 22.6% increase in liquid fuels consumption (2022.99.1 mbpd compared to 2050/121.5 mbpd). For natural gas, EIA projections for 2050 consumption compared to 2022 actuals show which show a 29.1% increase in consumption, the highest percentage increase by a substantial amount.

The 2023 IEA World Energy Outlook Stated Policies Scenario (STEPS) forecasts a decrease in global fossil energy demand due to policies, economic factors, and the 2022 global energy crisis This forecast reflects a shift towards clean energy technologies, with consumption of oil and coal dropping by 4.8% and 13.8% respectively between 2022 and 2050. Consumption of natural gas on the other hand, increases by 11.4% between 2022 and 2050. As noted, in 2022, natural gas is 24% of fossil fuel consumption. This compares to 17.9% for coal and 57.7% for oil. While the decline in oil and coal consumption is noteworthy, fossil fuel consumption in STEPS, including natural gas, remains highly problematic for meeting Net Zero targets. In IEA's Net Zero Scenario, natural gas consumption between 2022 and 2050 declines by 78.6%. Net Zero targets adopted by the world's countries are significant and discussed further in Section 3of this analysis. Suffice it to say that meeting these targets will require much more rapid adoption of clean energy sources and technologies and stronger government policies.

Demand for different fuels also exhibits significant regional disparities, as declining demand in advanced economies is, as noted, somewhat offset by the energy demand growth in many emerging and developing economies, especially for natural gas. Despite government policies and targets, energy security remains a concern and, according to the IEA's WEO, investments in oil and gas supply are still necessary.[22]

There are several reasons for the increased demand for natural gas in the near to mid-term in both the EIA reference case and the IEA's STEPS. There are abundant supplies of natural gas in the world, including unconventional gas, and many of these supplies can be developed and produced at relatively low cost.[23] Natural gas can be stored and transported either through pipelines or liquefied and sent via LNG tanker. Natural gas power generation has great value as a critical asset for responding to both seasonal and short-term energy demand, helping to manage the intermittency[c] of renewable generation. Natural gas can also be used as a backup power generation source for critical infrastructure and facilities in case of electrical grid failures.[24] Finally, natural gas is the least carbon intensive of fossil fuels, emitting about half the CO_2 when combusted relative to goal. All these factors make natural gas a flexible and generally reliable source of energy for the clean energy transition. In addition, and critical to this analysis, natural gas is a critical fuel for key industrial processes both globally and in the United States.

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[c] Intermittency – refers to the inconsistent production of energy at all hours from renewable energy sources.

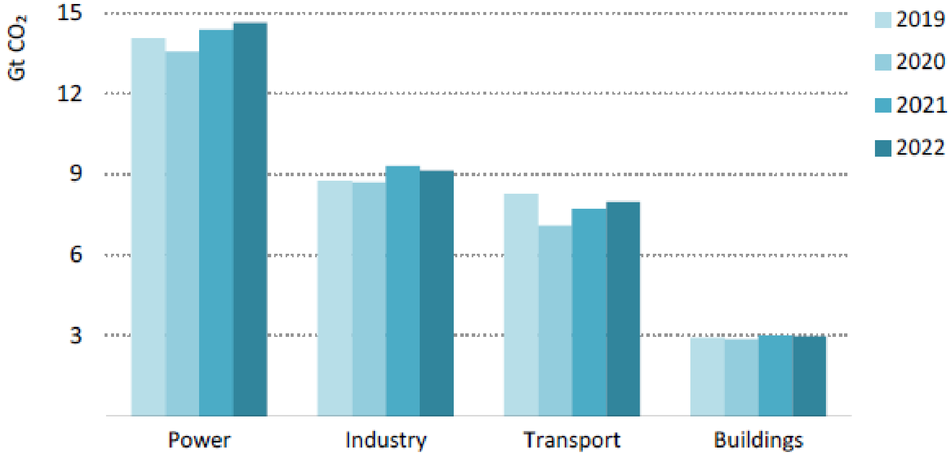
2. Decarbonizing the Industrial Sector: The Size of the Challenge

Industry is a leading GHG emitter averaging around nine $GtCO_2$ annually. Greenhouse gas emissions from the industrial sector are nearly one-quarter of global carbon emissions; the industrial sector will be one of the leading sources of increases in CO_2 emissions in the future, particularly for developing economies. The relative contribution of developing countries to industrial emissions has been increasing rapidly, with the highest growth rate of growth in industrial energy use occurring outside the OECD countries.

In 2019, approximately 79% of global GHG emissions came from the electricity, industry, transport, and buildings sectors, with around one fourth from the industrial sector. There have been some emissions reductions due to improvements in energy intensity of GDP[d] and carbon intensity of energy used but these reductions were less than the overall increase in emissions from the global use of fossil fuels.[25]

Since 2000, global industrial emissions have grown faster than emissions from any other sector; this has been driven by increased basic materials extraction and production and ince 2010, the GHG emissions from the industrial sector have increased by more than 30% (Figure 7).

Figure 7. Global CO_2 by Sector, 2019-2023



Source: IEA (2023), Emissions in 2022, IEA

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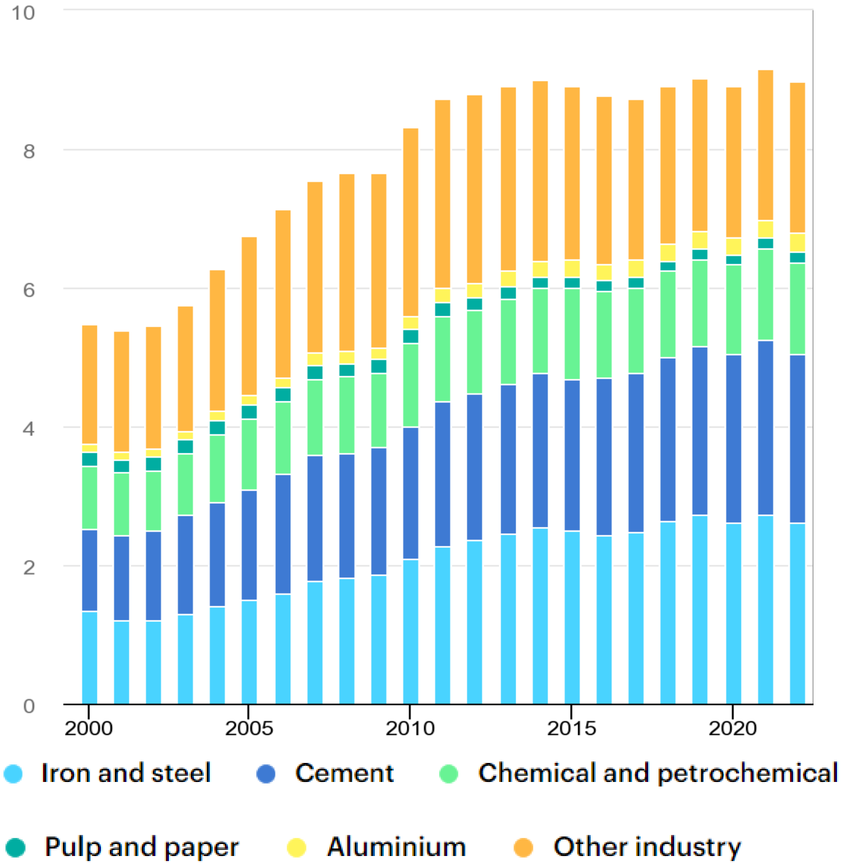
[d] Energy Intensity of GDP is the percentage decrease in the ratio of global total energy supply per unit of gross domestic product. The indicator is used to track the progress of energy efficiency. This IEA site tracks recent progress <https://www.iea.org/reports/sdg7-data-and-projections/energy-intensity>

Emissions from the industrial sector are primarily related to energy consumption, a wide range of industrial heat requirements spanning from 50 to 1,600℃ (122 to 2,912ºF), and the release of CO_2 during many industrial processes, including those for cement, lime, hydrogen, and manufacturing of other products. The largest contributors to industrial emissions in 2019 are seen in Figure 8.

Figure 8. Direct CO2 emissions from industry, 2000-22 (Gt CO_2)



Source: IEA, Tracking Industry

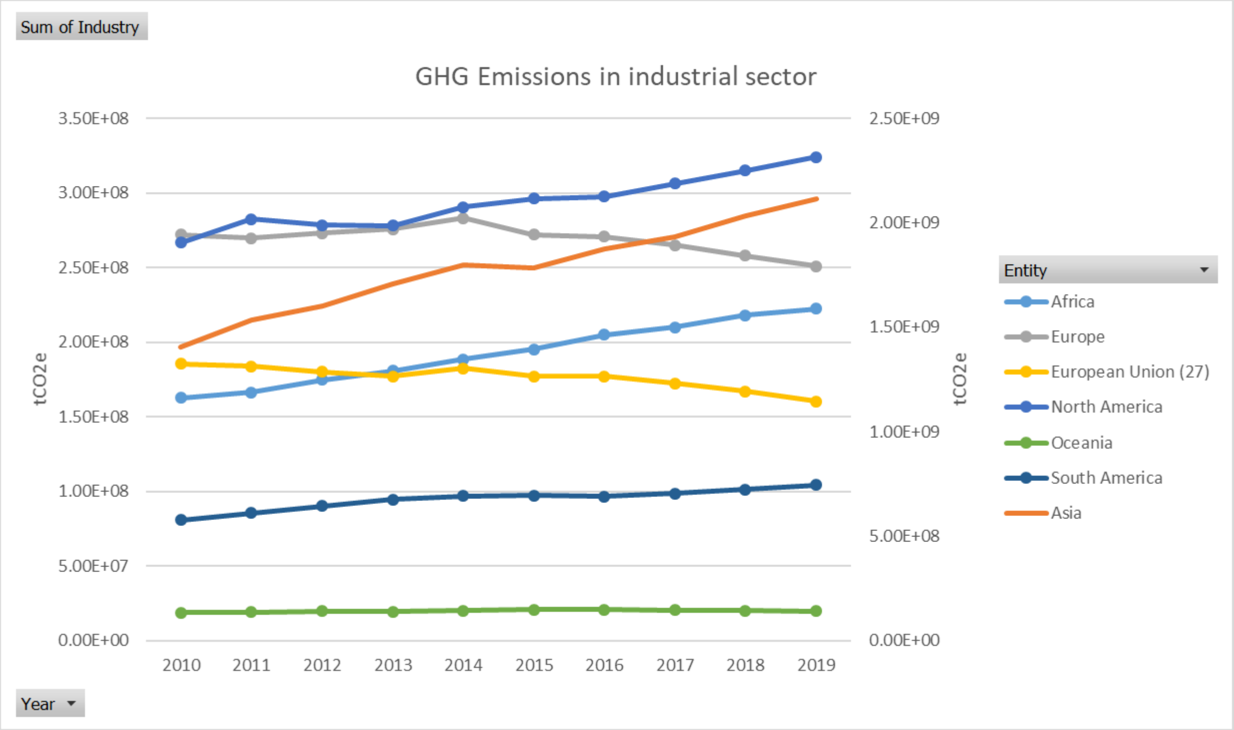
The following is the percentage share of global industrial emissions greenhouse gas emissions in gigatons of carbon dioxide equivalent from some key industrial subsectors, most of which rely on fossil fuels for heat, as feedstocks, and for electricity. Global energy-related CO_2 emissions were 36.8 Gt in 2022.[26,27] The industrial sector was responsible for 24.4% (8.98 Gt CO_2) of emissions in 2022, broken down as follows: [28]

- Iron and steel: 2.62 Gt CO_2 (7.1% total emissions)
- Cement 2.42 Gt CO_2 (6.6%)
- Chemical and petrochemicals 1.33 CO_2 (3.6%)
- Pulp and paper 0.15 CO_2 (0.4%)
- Aluminum 0.27 CO_2 (0.7%)

- Other 2.19 CO_2 (6%)

According to the International Energy Agency (IEA), global emissions from the industrial sector declined by 1.7% to 9.2 Gt in 2022. While several regions saw manufacturing curtailments, the global decline was largely driven by a 161 Mt CO_2 decrease in China's industrial emissions, reflecting a 10% decline in cement production and a two percent decline in steel manufacturing.[29] At the time, IEA noted that these numbers would likely rebound, tracking patterns seen in the period from 2010 to 2019, when greenhouse gas emissions from the industrial sector saw widespread increases (Figure. 9). Only Europe saw emissions declines in this period.

Figure 9. CO_2 emissions from Industry by Continent/Global Region (2010-2019)

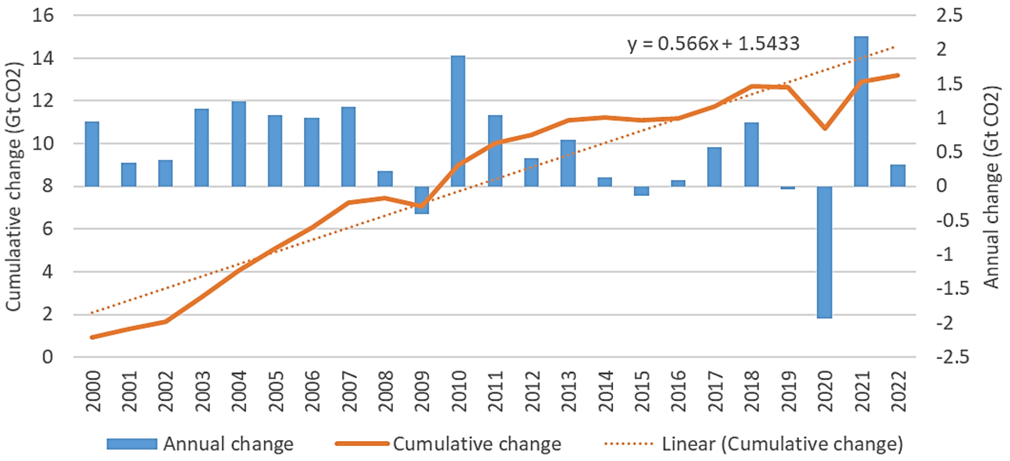


Source: Fonquergne and Balch, New Mexico Institute of Mining and Technology, Adapted with data from Ritchie, 2020.

Note: Right axis shows emissions for Asia, while the left axis is for rest of world.

Emissions declined by more than five percent in 2020, as the COVID-19 pandemic cut energy demand. Per IEA's forecast, emissions in 2021 rebounded past pre-pandemic levels, growing more than six percent as the global economy recovered and grew post-COVID (Figure 10).

Figure 10. Annual and cumulative change in global CO_2 emissions from energy combustion and industrial processes (2000-2022)



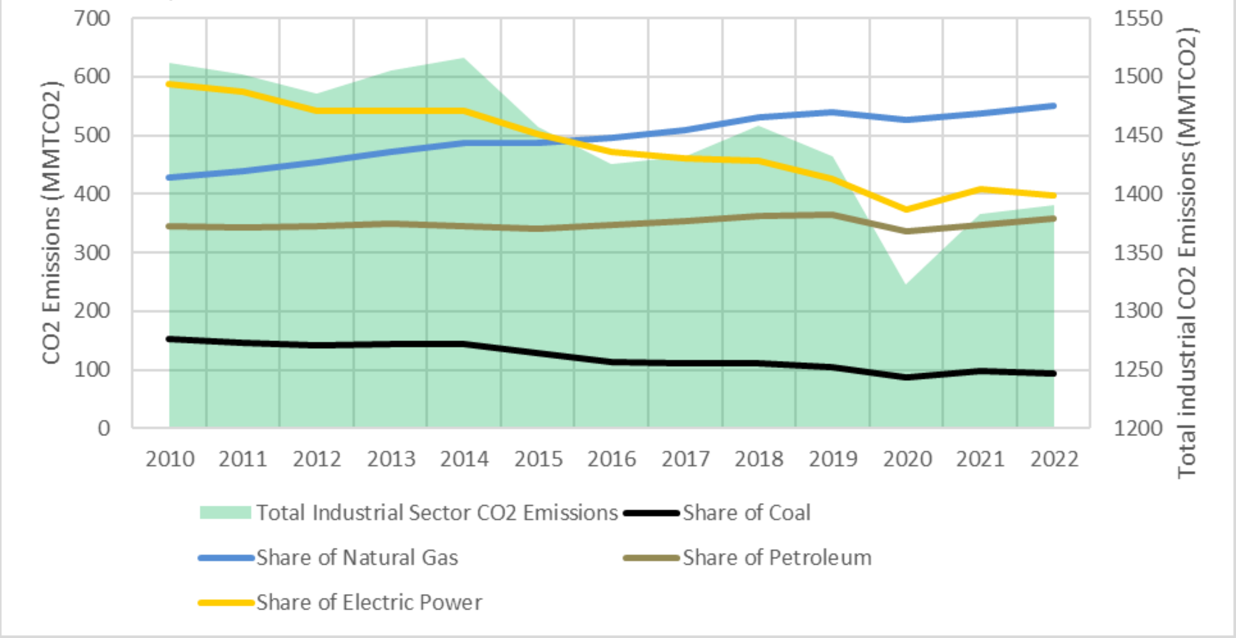
Source: Fonquergne adapted with data from IEA (2023), CO2 Emissions in 2022, IEA

Simulations and modeling suggest that the trajectory of industrial emissions heavily depends on the broader assumptions about emissions pathways. In all cases reviewed for this analysis, industry is set to become the largest emitting sector by 2035.[30]

While OECD countries are switching from coal and oil to lower carbon intensive energy sources, the same is not true for non-OECD countries, where the least expensive sources of energy and power will continue to dominate.[31] The investments needed to accelerate the clean energy transition could be significant in both OECD and non-OECD countries. The affordability and timescales for deployment of these emissions reduction technologies, however, could also limit their uses in non-OECD countries as these countries tend to be more focused on energy prices, industrial development, and the associated buildout of energy systems.

This shift towards decarbonizing electrical generation in some countries and regions has had a notable impact on global CO_2 emissions from the industrial sector. It's worth noting, however, that the portion of CO_2 emissions attributed to natural gas within the industrial sector continues to expand (Figure 11). This underscores the ongoing imperative to aggressively pursue decarbonization efforts within the natural gas industry.

Figure 11. CO$_2$ emissions from the US. industrial sector and energy/electricity shares, 2010-2022



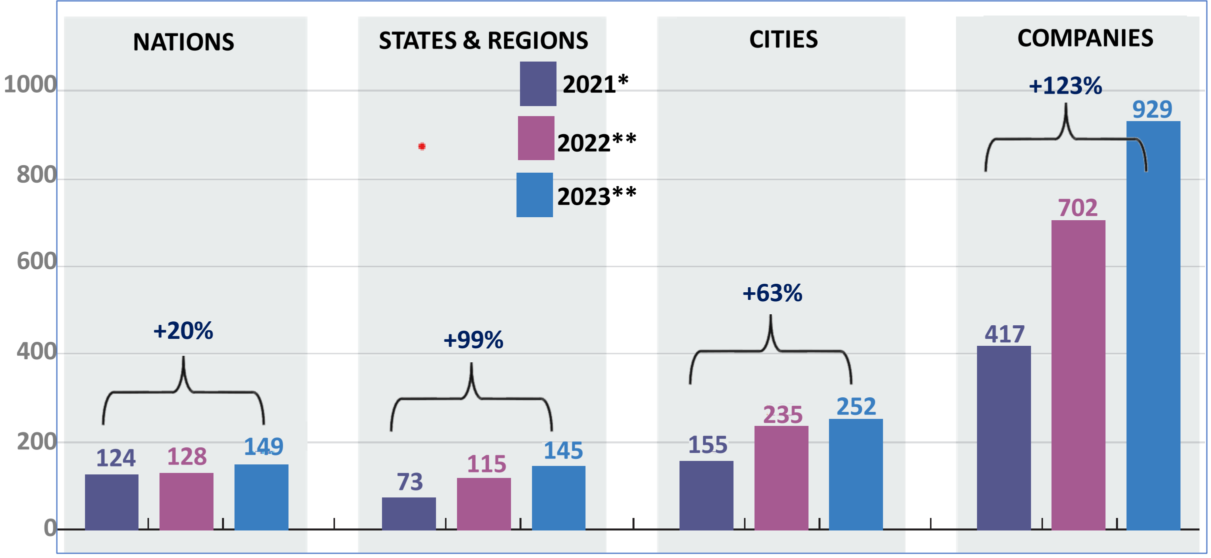
Source: Based on data from U.S. EIA; as modified by Fonquergne, New-Mexico Tech.

3. Net-Zero Commitments

Climate change is an existential threat and rapid decarbonization is essential. At the same time, the industrial sector, while a major emitter, is essential for global, regional, and national economies. Industrial products and processes are also critical components of the technologies that help enable the clean energy transition, e.g., wind turbines and transmission towers. In addition, affordability is key; added costs could affect the competitive position of exports and delay the transition. Thoughtful, sequenced policies are clearly needed to mitigate climate change.

Currently, the foundational drivers of industrial decarbonization efforts are growing commitments to net zero targets across the globe. While climate change is a global crisis, it is the responsibility of individual governments to define both the specific long-term and interim targets for meeting the 1.5° C target, and the corresponding national strategies. Within the framework of the Paris Agreement, 191 countries, representing over 90% of global CO2 emissions from energy and industrial processes, have submitted their Nationally Determined Contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC). These NDCs vary in terms of targets and the level of ambition, reflecting the diverse approaches taken by different nations.[32]

Figure 12. Net-zero Commitments/Pledges, 2021-2023



**Net Zero Stocktake 2022, Data: June 2022

**Net Zero Stocktake 2023, Data: Jume 2023

Source: Net Zero Stocktake June 2022, June 2023

The number of countries, states and regions, cities, and companies making pledges to reduce GHG emissions to net zero is on the rise (Fig. 12). In 2023, 149 countries, 252 cities, and very importantly, 929 companies (a 123% increase in a little over two years) have net zero targets; company targets include investors and could affect investments in energy systems. Including natural gas systems.[33] These commitments represent 88% of global emissions, 92% of global GDP, and 89% of global population.[34] At the same time, however, as discussed earlier, global CO2 emissions continue to rise, highlighting the need for more mechanisms and technologies to reduce emission.

Countries, regions, and industries that set climate targets, such as the reduction of greenhouse gas emissions by a certain percentage by a specific year, provide frameworks for action and accountability, that serve as models and could be replicated. Decarbonization objectives can, in part, be met through taxes, mandates, incentives, and investments. Implementing a carbon price through mechanisms like carbon taxes or cap-and-trade systems can, for example, encourage the adoption of cleaner technologies and practices. Another example: there have been significant and long-term tax incentives in the US for renewable generation that encourage both deployment and investment.

At the same time, providing financial incentives such as tax credits, grants, and subsidies for low-carbon energy sources and clean technologies can accelerate their deployment and adoption by making them cost competitive, though the burden of paying is given to the public. CCUS in the United States is, for example, supported by the 45Q tax credit. In addition, investing in research and development for CCUS can drive innovation and help develop scalable solutions for industrial decarbonization, though these changes can take decades to make it into standard practices at scale.

3.1. Policy and Regulation

To meet decarbonization targets, many countries are developing strategies to reduce industrial emissions. These strategies include: (1) investing in research and innovation to create new, low-carbon technologies, (2) establishing guidelines for energy and environmental standards, and (3) making commitments to meet climate goals.

As noted, greenhouse gas emissions from energy uses in industry account for 24.2% of the global GHG emissions.[35] In addition, direct industrial processes for chemicals or cement account for another 5.2% of global GHG's. This makes the industrial sector responsible for 29.4% of total GHG emissions.

To reduce greenhouse gases emissions, new policies and regulations have been adopted or proposed in many countries and regions that have significant implications for their industrial sectors. These policies and regulations include carbon pricing, financial incentives, research funding, emissions targets, and energy standards. Geopolitics and international affairs can dramatically impact the effectiveness of these policies and while many countries have net zero policies, have signed the Paris Accord, and are parties to Conference of the Parties

(COP) agreements,[e] some countries remain reticent about implementing policies that will increase energy costs or make their industries less competitive in global and regional markets.

3.2. Regulatory/Policy Drivers to Enable Decarbonization

Policy incentives and regulations are enablers of decarbonization, including those designed to guide the implementation of mandatory emissions targets, mandatory adoption of generation sources,[f] and efficiency standards. In 2023, 149 countries including the biggest emitters – China, the United States, and the European Union – have net-zero targets, covering about 76% of global emissions. These countries/regions have implemented standards or targets to promote the adoption and integration of clean energy sources into their energy mix. These standards may include specific goals for the percentage of energy that must come from low-carbon energy or pledges to take rigorous, immediate action to halve global emissions by 2030.[36]

Another approach is energy efficiency standards that establish regulations and set requirements for the energy performance of industrial processes with the aim of reducing energy consumption and promoting sustainability. Industrial decarbonization is also addressed by policy initiatives, such as green deals,[g] climate fight agreements,[h] and the development of transition plans for regions, nations, and high-emission industries.

Developing transition plans for industries with high emissions, such as coal and heavy manufacturing, can guide their shift towards more sustainable practices and technologies. For example, in the United States, the U.S. Department of Energy's Industrial Decarbonization Roadmap identifies key pathways for reducing industrial emissions through innovation in American manufacturing.[37] The key technology pillars identified in this roadmap are energy efficiency; industrial electrification; low-carbon fuels, feedstocks and energy sources; and carbon capture, utilization and storage.

The enactment of the Inflation Reduction Act of 2022 (IRA) in the United States, a significant legislative achievement for the clean energy transition, provides substantial financial backing for low-emissions technologies, including $5.8 billion for projects to reduce emissions from energy intensive industries, including iron, steel, concrete, glass, pulp, paper, ceramics, and chemicals.

The IRA also includes new, and extensions of existing, tax credits, for wind, solar and energy storage, contingent on project investment expenses and electricity generation (USD/MWh).

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[e] COP: The Conference of the Parties is the supreme decision-making body of the United Nations Climate Change Convention.

[f] To impose an industry or activity to use a certain power source – such as renewable generated power. This is usually done with a Renewables Portfolio Standard (RPS) which is a policy or regulatory mechanism that requires utilities and energy providers to obtain a specific percentage of their energy from renewable sources.

[g] A "Green Deal" is a comprehensive policy proposal that combines economic and environmental goals.

[h] "Climate Fight Agreements" refer to international agreements and commitments made by governments to combat climate change.

Additionally, it provides tax credits for local manufacturing and grid enhancements, as well as various other types of support, including CCUS.

On March 16, 2023, the European Commission introduced the Net-Zero Industry Act (NZIA), aimed at bolstering Europe's manufacturing capabilities for net-zero technologies, surmounting obstacles to scaling up manufacturing in the region, enhancing the competitiveness of the net-zero technology sector, and reinforcing the EU's energy resilience. This proposal underscores Europe's dedication to spearheading the transition toward net-zero technologies and contributing to the achievement of the Fit-for-55 and REPowerEU goals.[38]

The European Union (EU) has developed an Emission Trading System (ETS) that places a price on carbon emissions and encourages industries to reduce their greenhouse gas emissions, indirectly incentivizing cleaner natural gas technologies. Also, the EU has set renewable energy targets to increase the share of renewable energy sources in the energy mix, which can affect natural gas consumption within its borders. In addition, the EU is actively working on the development and implementation of a Carbon Border Adjustment Mechanism (CBAM) as part of its broader climate policy framework.[39]

The CBAM, designed to go into effect in 2026, is another EU policy tool designed to specifically address carbon leakage and promote climate action by placing tariffs on certain imported goods based on their carbon content. This import tax is imposed on importers when these products enter the EU. The CBAM's goal is to help ensure that imported products are subject to a carbon pricing mechanism like those imposed on domestic products, thereby preventing companies from relocating production to countries with lower environmental standards to avoid emissions regulations. The goods covered by the CBAM are cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen, all of which are either made or generated with substantial volumes of fossil fuels, including natural gas. Other regions and countries have also expressed interest in similar mechanisms. Notably, this mechanism involves acquiring certificates representing the carbon emissions embedded within the goods.

The pricing of these certificates will be determined by referencing the prevailing carbon price within the EU ETS.[40] On 16 May 2023, the CBAM Regulation was published in the EU's Official Journal. Over a period of eight years, CBAM will also gradually replace the free allowances given under the EU Emission Trading System (ETS).[41]

Other countries, and smaller administrative units, have policies on carbon pricing mechanisms and incentives for emissions reductions that affect or could affect natural gas supply and demand. These policies demonstrate the variety of approaches taken by different countries to balance natural gas development with decarbonization efforts. Canada has implemented a carbon pricing system, which includes a carbon tax in some provinces. This incentivizes industries to reduce emissions, including those from natural gas operations. California and Quebec linked their cap-and-trade systems in 2014. The system covers fossil fuel combustion and industrial emissions in power, buildings, transport, and industry. The resulting carbon trading market is now the largest in North America and has generated revenue of over $7.3 billion for Quebec.[42]

Specific to natural gas, China provides subsidies for the use of natural gas in place of coal for heating and power generation, with a focus on improving air quality. These subsidies cover equipment installation costs and fuel prices. These incentives are projected to grow China's natural gas import demands by 16 Tcf by 2050. China is also on a trajectory to continue coal use at increasing levels through 2030. Norway also has developed a hydrogen strategy to utilize natural gas in hydrogen production while capturing and storing carbon emissions.

At the same time, the U.S. has provided tax incentives for oil and gas exploration and production. At a national level there have been discussions, however, about reducing these incentives to promote cleaner energy sources. As noted, the IRA and the expansion to the 45Q tax credit has increased interest in industry addressing decarbonization projects, primarily through carbon use and storage. First introduced in 2008, Section 45Q of the United States Internal Revenue Code provides a tax credit for CO2 storage. The tax policy is intended to incentivize deployment of CCUS, and a variety of project types are eligible, including natural gas projects.

Also, some states are incentivizing renewable natural gas (RNG) production from organic waste sources and its transport via existing natural gas pipelines. RNG production costs are substantially offset by federal and state policy incentives, though scaling these sources to the equivalent scale of fossil natural gas would be a significant technical and infrastructure challenge. In addition, California's Low Carbon Fuel Standard (LCFS) program has incentivized growth in RNG projects both inside and outside the state, resulting in an uptick in RNG fuel crediting in recent years demonstrating that local changes at least have the potential to carry past borders.[43]

3.3. The EU Carbon Border Adjustment Mechanism: Sectoral Impacts of Decarbonization Policies

While the transition to a low-carbon economy is crucial for addressing climate change, there are concerns about how decarbonization policies, such as CBAM, might affect key industries, weaken European industrial competitiveness, and increase economic risks posed by EU standards.[44] Industries that are energy-intensive may face higher energy costs due to the shift toward renewable energy sources and the implementation of carbon pricing. At the same time, the costs associated with decarbonization efforts, such as subsidies and energy-efficiency upgrades, would be passed on to consumers in the form of higher prices on goods or in higher taxes. Concerns have been raised that this could make industrial manufacturing subsectors in the EU less competitive in global markets, potentially leading to a loss of market share and eventually a loss of jobs.

The CBAM may also shift carbon intensive industries to other countries with less stringent emissions standards and requirements. As an example, the impact of CBAM on global emissions depends on the responses of companies and nations. Given the substantial size of the developed countries' markets (such as the EU market), there will be a significant pull towards products with reduced emissions intensity. Whether this amplified demand for low-carbon-intensive products will stimulate increased production to meet growing global markets or if other governments will implement demand-driven policies remains to be determined.

The EU CBAM aims to ensure equitable competition for energy-intensive industries within the EU, promote emissions reduction efforts in countries both within and outside the EU, and mitigate the risk of carbon leakage from the EU market. However, responses from certain major economies suggest that the CBAM could face considerable international resistance, particularly from nations heavily reliant on fossil fuels. Overland and Sabyrbekov, in an Energy Policy article, analyzed the countries that are most likely to have negative views of the CBAM, incorporating various factors such as trade volume with the EU, carbon intensity of industries, domestic public sentiment regarding climate change, and innovation capacity (Figure 13). The EU's ability to effectively manage opposition from these countries will play a pivotal role in determining the fate of the CBAM.[45]

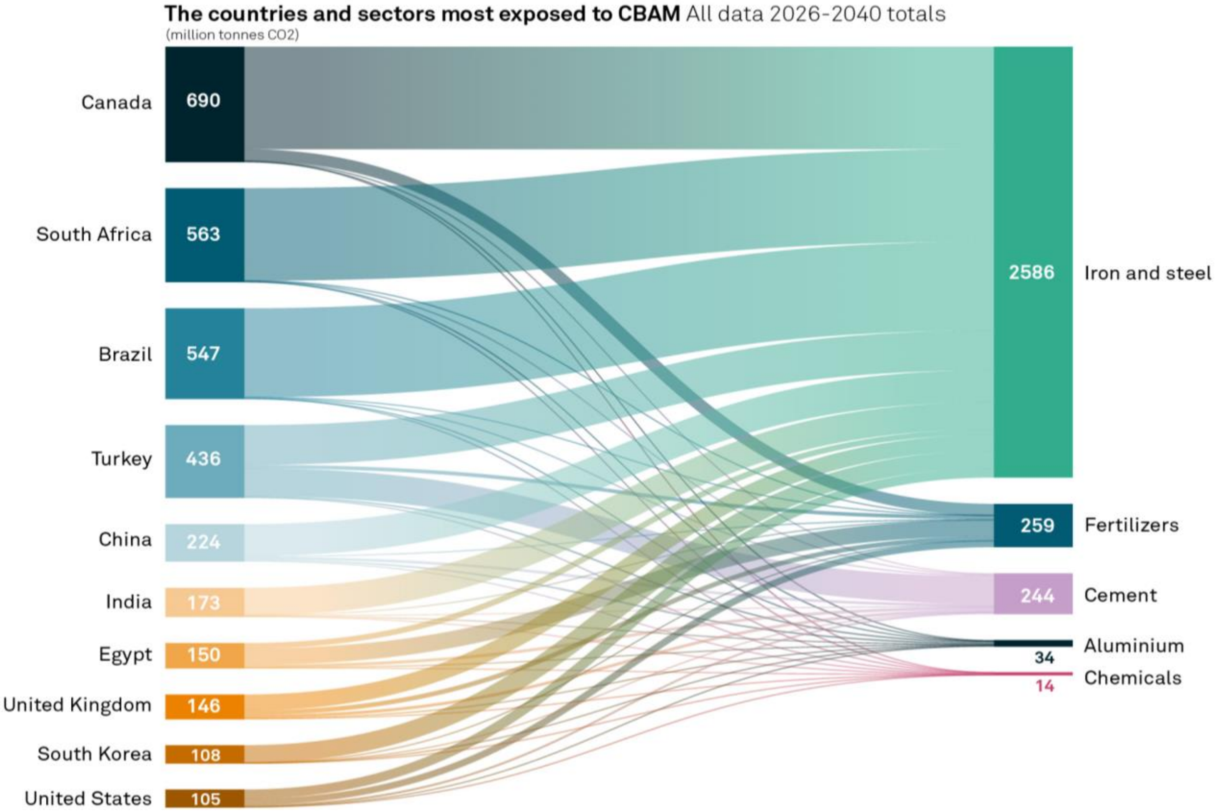
Figure 13. Countries/Regions that Could Have Negative Views of the EU's CBAM

Source: Overland, I., & Sabyrbekov, R. (2022). Opposition Index appendix to Know your opponent: Which countries might fight the European carbon border adjustment mechanism? Energy Policy, 169, 113175.

According to this analysis, the following nations are most inclined to vigorously resist the CBAM: Iran, Ukraine, the United States, the United Arab Emirates, Egypt, China, India, Kazakhstan, Russia, and Belarus. Analysis by S&P Global Commodity Insights concludes that a different set of countries -- Canada, Brazil, South Africa, and Turkey will be most impacted by CBAM, with the iron and steel subsectors experiencing the greatest impacts of targeted industrial subsectors (Fig. 14).[46] These sectors are large consumers of natural ga s for power and heat generation.

There is a clear downside risk to global market segmentation, with cleaner products primarily directed towards Europe and other developed markets (especially OECD). At the same time, emissions-intensive products will be exported to developing and emerging markets (primarily non-OECD). Such a scenario, by shifting rather than eliminating emissions from the manufacturing/production of key industrial goods, could be incompatible with the global goal of achieving net-zero emissions (NZE).

Figure 14. Countries and sectors most exposed to EU CBAM (all data are 2026-40 totals)



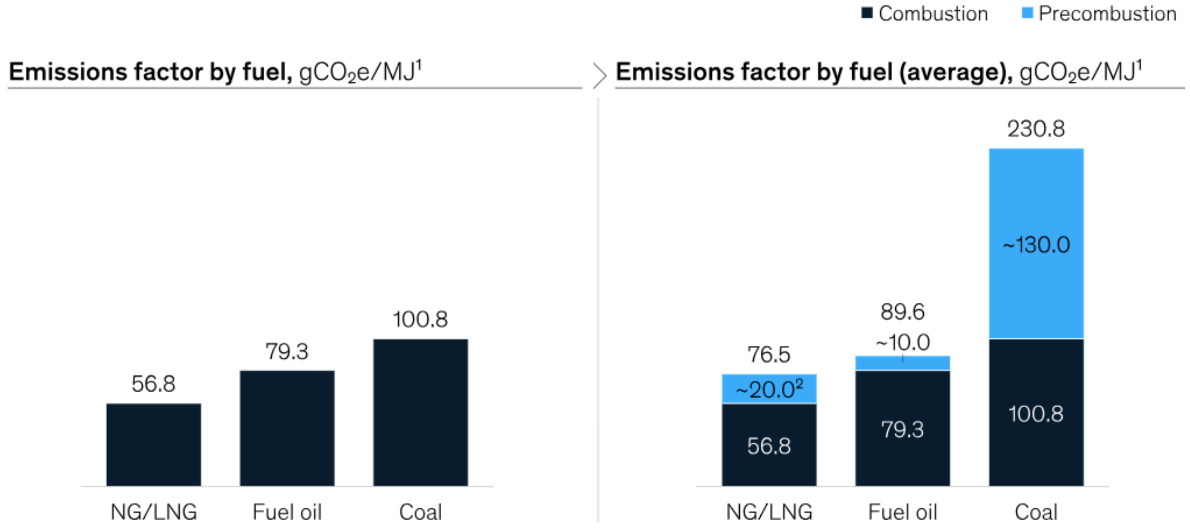
Source: Eklavya Gupte (2023). Infographic: Developing economies hit hardest by EU's carbon border tax, S&P Global, Commodities Insight.

Until now, the industrial sector in the EU has been shielded from the effects of climate policies and carbon pricing mainly due to concerns about global competitiveness and the potential for the carbon footprint simply being transferred to another geography.[47] However, new approaches in industrial development policies are emerging to facilitate the transition to net-zero greenhouse gas emissions. This transition hinges on several factors: a clear commitment to achieving net-zero emissions, advancements in technology, a growing market demand for low-carbon materials and products, effective governance capabilities and learning, inclusive plans for workforce transition, and international coordination between climate and trade policies. It necessitates comprehensive and step-by-step industrial policy strategies that involve immediate action and readiness for future decarbonization efforts. Furthermore, these strategies should be adaptable to different governance levels, from international to local, and should be integrated with other policy areas.[48]

4. Greenhouse Gas Emissions from Natural Gas

To analyze the role of natural gas in industrial decarbonization, it is important first to understand gas greenhouse gas emissions relative to other fuels. When the energy units are normalized, natural gas is the cleanest burning of fossil fuels (Figure 15), with slightly more than half the emissions of coal. Natural gas has a lower carbon intensity and lower particulate emissions per unit of energy than fuel oil or coal. Natural gas generates lower emissions per unit of energy than coal or oil, both before and during combustion. In China, for example, some coal boilers near cities have been replaced with gas boilers to locally reduce pollution and alleviate public health issues. As such, it is highly likely that it will be needed to help enable the clean energy transition.[49]

Figure 15. Fossil fuel emissions factor by fuel (gCO2e/MJ)

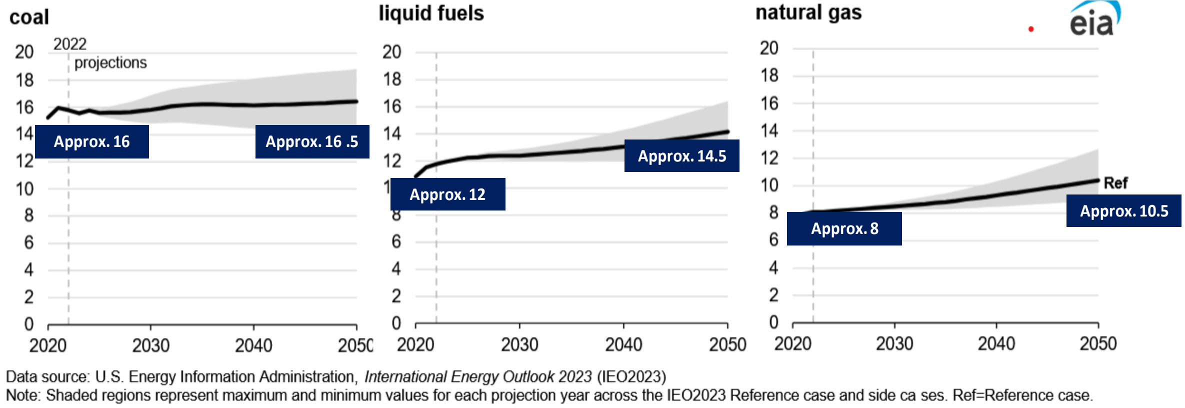


[1] Grams of carbon-dioxide equivalent per megajoule.
[2] Weighted average GHG emissions of 2016 LNG flows into China, including 13 projects: APLNG, Atlantic, Gorgon, Malaysia, Nigeria, Oman, PNG, Qatargas, QCLNG, Snohvit, Sabine Pass, Tangguh, and Yamal.

Source: Agosta A., Boccara G., Bresciani G., Heringa B., Browne N. (2021). The impact of decarbonization on the gas and LNG industry, McKinsey & Company.

Natural gas, however, still represents a significant portion of the global CO_2 emissions from fuels (Figure 16). Based on the forecast these estimates (volumes in the figure are estimates made by EFIF analysts), in 2022, CO2 emissions from coal were 44.4% of total fuels emissions, liquid fuels were 33.3% of the total, and natural gas was 22.2% of the total emissions from fuels. The EIA's reference case projection in 2050 shows an absolute increase of 8.7% CO2 emissions from liquid fuels. Emissions from coal increase slightly, from oil by 20.8%, and from natural gas by 31.25%. The increase in natural gas emissions reflects the overall increase in natural gas demand. It also demonstrates the significant need for emissions reductions from natural gas, including from alternatives and from technologies where alternatives are not available or affordable.

Figure 16. Global CO2 Emissions by Fuel, EIA Reference Case, 2022-2050 (proj.), billion metric tons



Data source: U.S. Energy Information Administration, International Energy Outlook 2023 (IEO 2023)

Note: Shaded regions represent maximum and minimum values for each projection year across the IEO2023 Reference case.

The global drop in emissions associated with COVID-19 appears to have ended. According to the IEA Gas Market Report, in 2022, global CO_2 emissions from energy sources surged by 321 million tons, surpassing a new record of 36.8 billion tons, with a substantial increase of 423 million tons from energy combustion, while emissions from industrial processes dropped by 102 million tons. In addition, although natural gas emissions had only decreased by a marginal 0.09% between 2020 and 2021, they experienced a more significant reduction of 1.6% (118 million tons) between 2021 and 2022 due to supply constraints exacerbated by the Ukraine conflict, especially pronounced in Europe (-13.5%) and Asia (-1.8%). These declines, however, were outweighed by rising emissions from coal and oil, driven by a shift from gas to coal in some regions.[50]

As noted earlier, industrial sector emissions are attributed to a combination of sources, including:

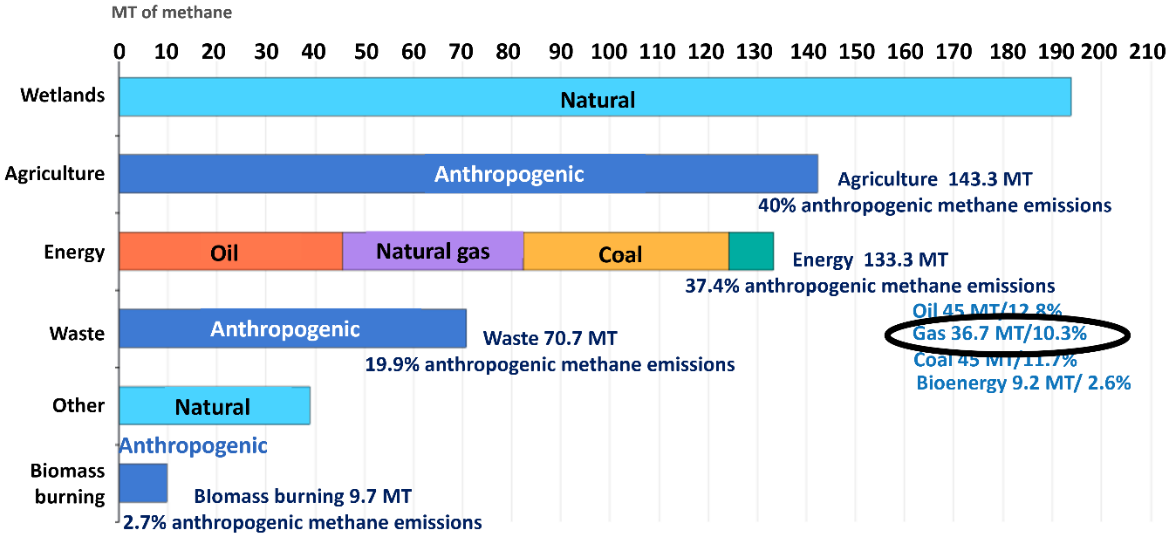
- **Fuel-Related Emissions**: Emissions associated with the combustion and use of fuels at industrial facilities for needs other than electricity (e.g., for process heat)
- **Emissions from Power Generation**
- **Industrial Process Emissions**: non-energy-related process emissions from industrial activities (e.g., direct CO_2 or other GHG emissions from chemical transformations in materials being processed)

- **Manufactured Product Life Cycle Emissions:** emissions generated upstream of the manufacturing processes (supply chain, life cycle) and downstream (during product use and end of life).

4.1. Industrial Decarbonization and Greenhouse Gas Emissions

In addition to emitting CO2, natural gas also emits significant volumes of methane, a much more powerful greenhouse gas than CO2, albeit with a lifespan in the atmosphere of about 0.1% that of CO2. Global methane emissions and their sources are seen in Figure 17. According to the IEA, in 2022, natural gas was responsible for 10.3% of total anthropogenic methane emissions. Globally, it is the second lowest source of anthropogenic methane emissions; only biomass burning is lower.

Figure 17. Amounts/Sources, Percentages of Global Methane Emissions, 2022



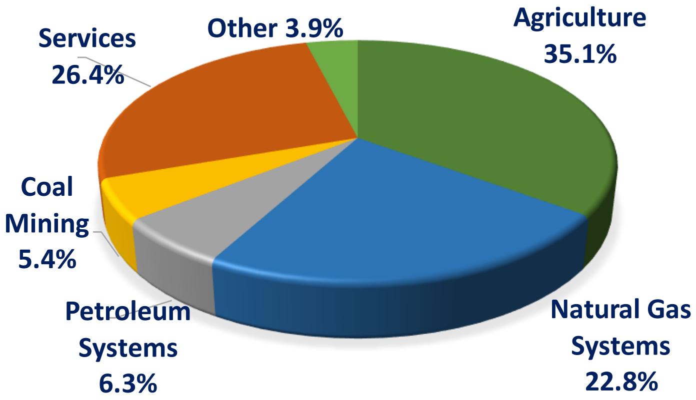
Source: IEA, Global Methane Tracker 2023

The story in the U.S. is different, reflecting higher levels and percentages of natural gas consumption and production (the U.S. leads the world in natural gas production) compared to the rest of the world. Figure 18, based on EPA data, shows that natural gas is almost 23% of U.S. anthropogenic methane emissions compared to just over 10% globally. It is also the third largest source of emissions, although much lower than emissions from agriculture and slightly lower than those from services, e.g., landfills.

These reductions are attributed in part to efforts by the natural gas industry to capture their methane emissions although much more needs to be done. Reducing methane emissions from gas systems could have a major impact on lowering overall greenhouse gas emissions from the industrial sector.

Figure 18 from the U.S. Environmental Protection Agency (EPA)_shows where in gas production and distribution industry's efforts (in the United States) should be focused to reduce methane emissions from gas systems. Actions in this regard are critical. In 2022 a U.S. National Oceanic and Atmospheric Administration (NOAA) report noted that "Methane rose by 14 parts per billion to 1,911.9 ppb in 2022. It rose slightly faster in 2020 (15.20 ppb) and 2021 (17.75 ppb)."[51]

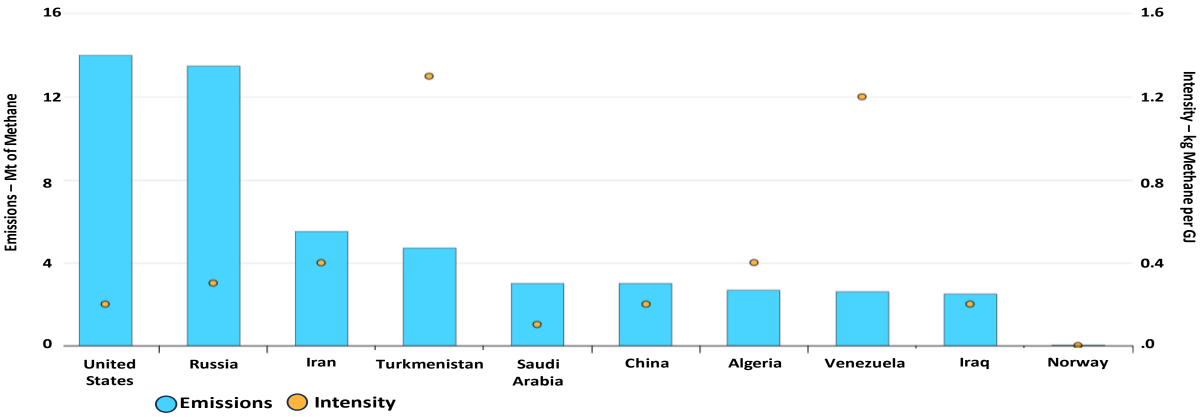
Figure 18. Sources/Percentages, Anthropogenic U.S. Methane Emissions, 2021



Source: EPA DRAFT Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021

Figure 19 shows methane emissions associated with oil and gas production for select countries.[52] The U.S. had the highest total emissions, with Russia a close second. From an emissions intensity perspective however (kg methane/GJ), only Saudi Arabia and Norway had lower emissions intensity than the United States.

Figure 19. Oil and Gas Methane Emissions Intensity of Production in Selected Countries, 2022



Source: IEA Global Methane Tracker, 2023

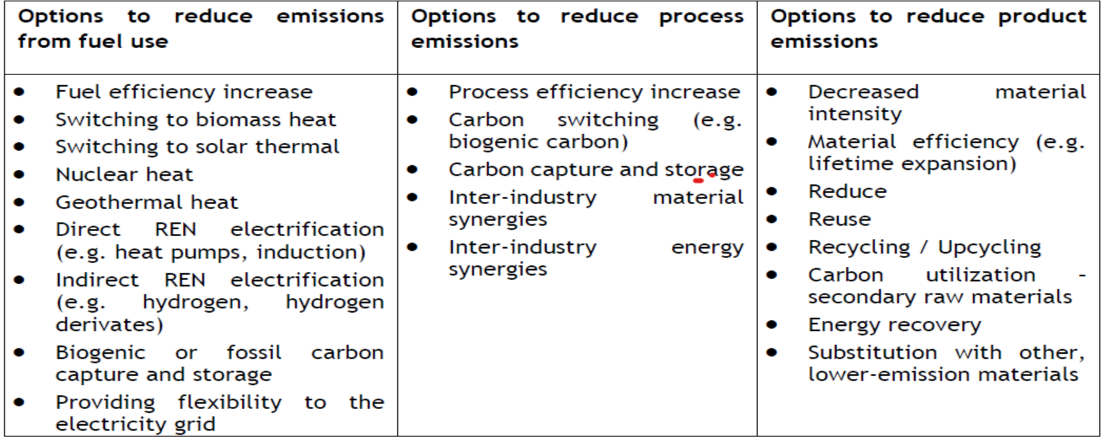
Importantly, IEA noted in its Global Methane Tracker report that, “Oil and gas methane emissions represent one of the best near-term opportunities for climate action because the pathways for reducing them are well-known and cost-effective. Even if there was no value to the captured gas, almost all available abatement measures would be cost effective in the presence of an emissions price of only about 15 USD/tCO_2-eq.”

In this regard, the industry in the United States is actively working to reduce these emissions and has made progress in view of its position as the number one producer of natural gas in the world. According to the EPA, methane emissions from U.S. gas systems fell by 16% between 1990 and 2021 (215.1 mmtCO2e in 1990 and 181.4 mmtCO2e in 2021). According to the EIA, U.S. natural gas production increased by almost 94% over the same 30-year time period (1,631 bcf/yr. to 3,529 bcf/yr.) In view of addressing the urgency of climate change, much more needs to be done to mitigate/eliminate these emissions but it is apparent that progress is being made. Importantly, the IRA includes a Methane Emissions Reduction Program and 1.55 billion in grant and technical assistance funds to reduce methane emissions from petroleum and natural gas systems.[53] This funding is very important for helping to reduce methane emissions from natural gas productions and systems in the United States. IEA estimates that to achieve the targets in its Net Zero Scenario, the oil and gas industry will have to spend about $75 billion between 2022 and 2030, less than 2% of the net income earned by the industry in 2022. Methane abatement could generate revenues of around $45 billion by 2030 from the sale of captured gas.[54]

5. Decarbonization Options for Reducing Gas Emissions in the Industrial Sector, Including Alternatives

The transition to a decarbonized energy system will, in the near to mid-term require a wide range of industrial products. The aluminum and steel industries support the manufacture of wind turbines, solar panels, electric grid components, electric vehicles (EV), and other zero and low-carbon infrastructure. All these products are produced through high-heat industrial processes, such as concrete, carbon fiber, glass, and steel. These materials are also needed for the infrastructure needed for the clean energy transition. The Princeton Net Zero study concludes that the U.S. will need to increase the capacity of its long-distance transmission lines by approximately 60% to connect wind and solar projects by 2030.[55] Analysis suggests this could require, at a minimum, 360,000 towers, to support these lines, which are made from steel, aluminum, and copper. Related, a European Commission funded study estimated the material requirements for the main types of wind turbines, utilizing concrete foundations require between 243 to 413 tons of concrete per megawatt (MW).[56] Thus incremental costs for industrial decarbonization will flow through to the raw materials needed for renewable energy resources.

Figure 20. Overview of Emission Abatement Options for Different Carbon Streams in High-Temperature Industrial Processes



Options to reduce emissions from fuel use	Options to reduce process emissions	Options to reduce product emissions
• Fuel efficiency increase • Switching to biomass heat • Switching to solar thermal • Nuclear heat • Geothermal heat • Direct REN electrification (e.g. heat pumps, induction) • Indirect REN electrification (e.g. hydrogen, hydrogen derivates) • Biogenic or fossil carbon capture and storage • Providing flexibility to the electricity grid	• Process efficiency increase • Carbon switching (e.g. biogenic carbon) • Carbon capture and storage • Inter-industry material synergies • Inter-industry energy synergies	• Decreased material intensity • Material efficiency (e.g. lifetime expansion) • Reduce • Reuse • Recycling / Upcycling • Carbon utilization - secondary raw materials • Energy recovery • Substitution with other, lower-emission materials

Source: Decarbonizing industrial process heat: the role of biomass. Olle Olsson1 & Fabian Schipfer2, IEA Bioenergy Task 4, December 2021

The IEA has identified a range of technologies that could abate emissions from the industrial sector, delineating the options but the different components of industrial processes, e.g., fuel use, process emissions, and emissions from the use of the product (Figure 20). This list is extensive but does not identify the status of the options (available, in development, early stage, etc.) nor does it address the costs or time scales associated with the deployment or use of these technologies. Nevertheless, the list provides areas where additional inquiry could provide valuable information to inform pathways for industrial decarbonization.

As seen earlier in Figure 3, technologies currently exist for temperatures as high as 1000° C, including electrification and efficiency. These technologies will decrease fuel use in the industrial sector, with corresponding decreases in greenhouse gas emissions.

There is a suite of technologies in development that are of interest for this study. These include electric boilers that commonly employ resistive heating elements powered by electricity to generate heat efficiently. These boilers are equipped with thermostats to control the flow of electric current and regulate heating. The heat produced by electric boilers can be used to heat water for generating steam in industrial processes.[57] In larger electric boilers, such as electrode boilers, electricity is directed through water streams to produce steam. A significant advantage of electric boilers is their exceptional efficiency, with nearly 100% electricity conversion into heat and minimal radiation losses from exposed boiler surfaces.[58] Moreover, electric boilers tend to have a lower capital cost, approximately 40% less than equivalent natural gas-fired boilers.[59]

Another technology, electric arc furnaces that melt metal through direct and radiant heating methods. This process involves electrical arcs generated when electricity leaps from an energized electrode to a grounded (neutral) one, resulting in high-voltage electric arcs.[60] These furnaces are used for producing roughly 30% of the world’s steel and are also used for melting steel for recycling. Notably, electric arc furnaces are considerably more energy-efficient than blast furnace-basic oxygen methods, the primary method for producing steel.[61] Indirect electrification is a process that uses renewable electricity to produce hydrogen via water electrolysis into oxygen and hydrogen, which is then used as a substitute for natural gas in thermal industrial processes.

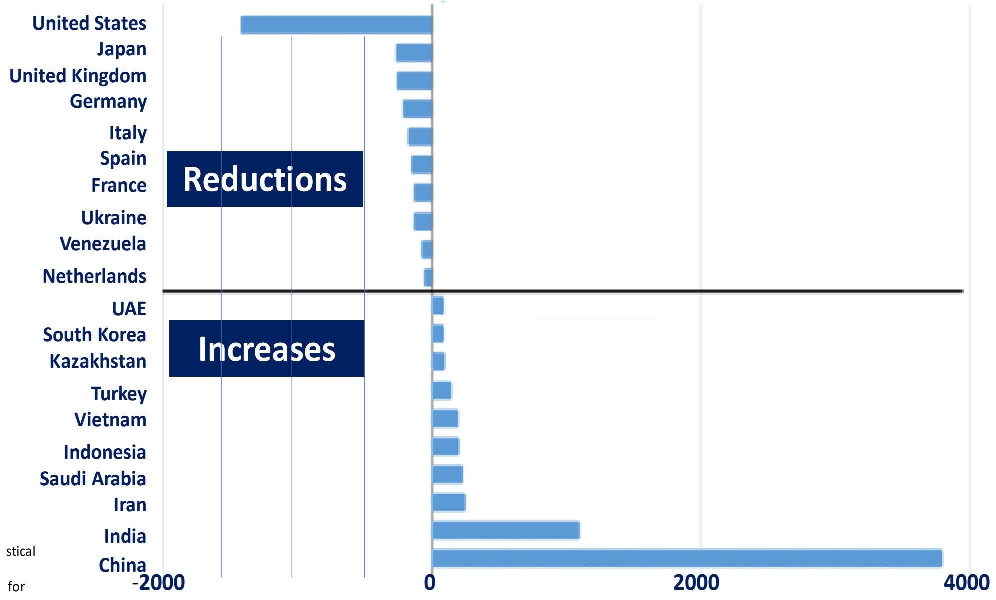
Not all industrial processes, however, can be electrified and as noted, fuels are needed to meet the high-heat requirements of many of these processes. The urgent need to accelerate the clean energy transition suggests that policies to accelerate the deployment of these technologies and practices are needed and essential for industrial decarbonization. Clearly, there is a need for a range of options for decarbonizing the industrial sector. This section highlights decarbonization options that are most relevant and achievable in the near- to mid-term that will either replace natural gas or enable its ongoing use in the clean energy transition. These include electrification, fuel switching, carbon capture, hydrogen, and a range of efficiency options.

The U.S. Department of Energy (DOE) projects fuel mixes used in the U.S. cement industry to change by shifting to lower-carbon fuels. For example, in the Near Zero GHG scenario, DOE assumes the coal consumption in the U.S. cement industry will be reduced from 52% to two percent, and petroleum coke use will be reduced to zero between 2015 and 2050. Natural gas, on the other hand, which has much lower CO_2 emissions, will likely be the substitute these two fuels for industrial processes that cannot be electrified.[62] This will increase U.S. natural gas demand, while reducing its export capacity, and does not have a carryover effect to countries lacking natural gas resources.

5.1. Electrification

Electricity represents a significant percentage of energy use by the industrial sector and as discussed earlier, is an option for reducing industrial emissions by electrifying some processes that currently use fuels. Importantly, in the U.S., there has been a marked decline in the overall CO_2 emissions from the power sector. This trend primarily stems from the phased-out use of coal as a major electricity generation source and an increase in zero-emissions renewable generation (Figure 21). Since 1990, natural gas generation in the U.S. has gone from 12.3% of the total to 38% and net zero generation from 31.1% to 39.4%. This has enabled the U.S. to lead the world in emissions reductions.

Figure 21. 10 Countries with Largest Reductions and Increases in CO Emissions, 2005-2020 (million metric tons)



Source: BP Statistics Review of World Energy, Institute for Energy Research

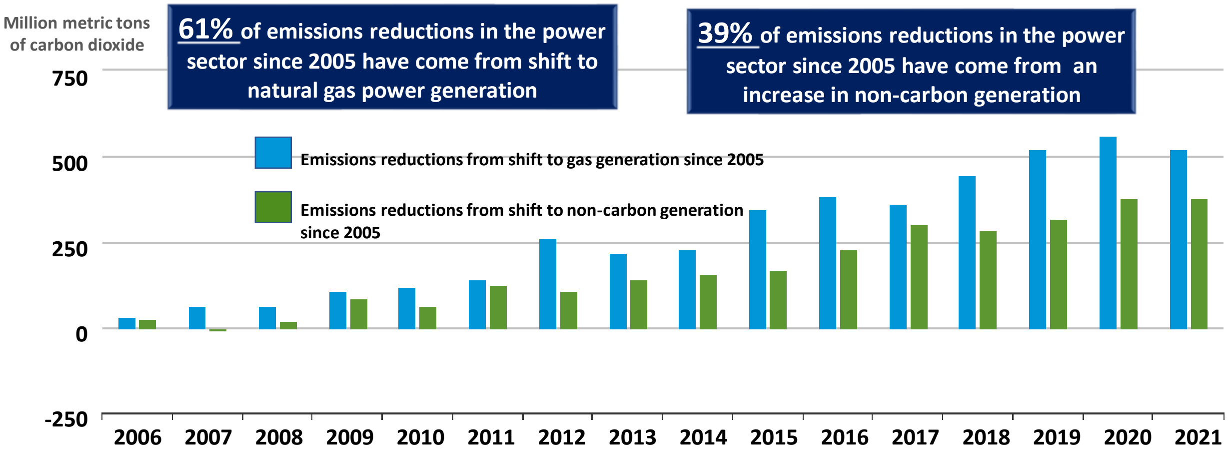
Electrification has the potential to play a crucial role in decarbonizing the industrial sector by replacing traditional, carbon-intensive processes and energy sources with cleaner and more sustainable alternatives. Of all the fuel that industrial companies use for energy, a McKinsey report[63] estimates that almost 50% could be replaced with electricity using available technology.

Industrial electrification, however, involves converting machinery, equipment, and processes to electricity to integrate renewable energy sources and energy-efficient technologies to minimize environmental impacts and increase energy efficiency. Industrial electrification will also require new or modified infrastructure in addition to the infrastructure needed for the fuels needed for the high-quality process heat that cannot be produced via electricity.

5.2. Fuel Switching

Substantial emissions reductions can be achieved from switching from coal to natural gas fuel, both as a fuel and for electricity. The U.S. has been the world leaders in this area, which is not surprising given its significant gas production and the age of its coal plants. Figure 22 shows the emissions reductions in the U.S. power sector enabled by coal to gas fuel switching between 2005 and 2021, where 61% of reductions have come from this transition.

Figure 22. CO_2 Emissions Reductions from Change in Fuel Mix for US Power Generation, 2005-2021

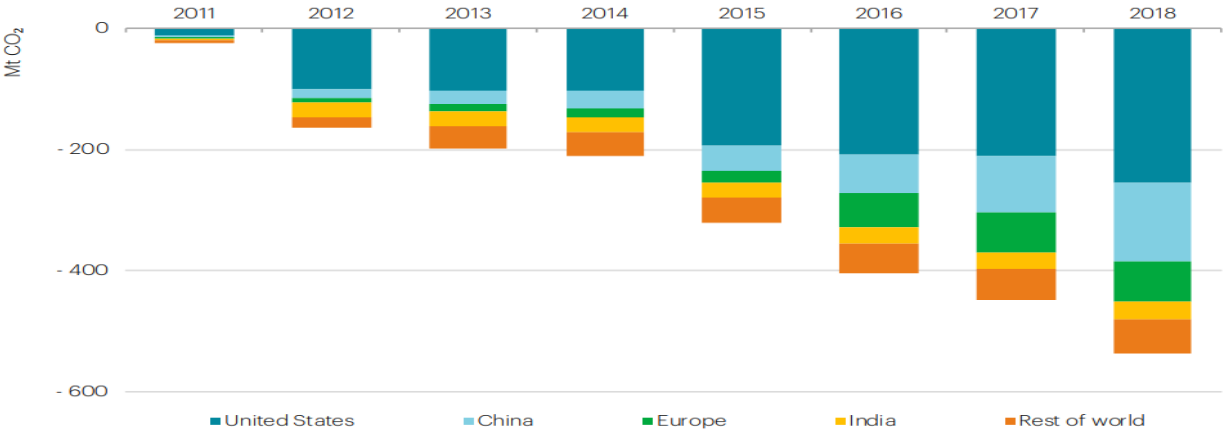


Source: EIA

As renewable energy costs decrease, they could challenge the role of natural gas and alter its significance in certain U.S. states, such as California. Renewables and energy storage solutions can potentially replace natural gas in some regions although, as noted by the IEA, these remain very expensive options when the cost of storage is included. It is more likely that for the foreseeable future, natural gas and renewable power generation will be complementary, with natural gas providing the base-load power to manage the intermittent wind and solar sources and the limitations of battery storage. In view of the urgency of climate change, the argument for rapid emissions reductions through coal-to-gas substitution is compelling, especially until affordable long duration storage technologies are available to manage the reliability issues associated with wind and solar generation.

As seen in Figure 23, China and other countries and regions of the world have also achieved significant reductions from coal to gas fuel switching. According to IEA, “Since 2010, coal-to-gas switching has saved around 500 million tons of CO2 - an effect equivalent to putting an extra 200 million EVs running on zero-carbon electricity on the road over the same period."

Figure 23. CO_2 savings from coal-to-gas switching by country/region, 2010-2018



Source: IEA (2019b), The Role of Gas in Today's Energy Transitions, IEA, Paris https://www.iea.org/reports/the-role-of-gas-in-todays-energy-transitions, License: CC BY 4.0

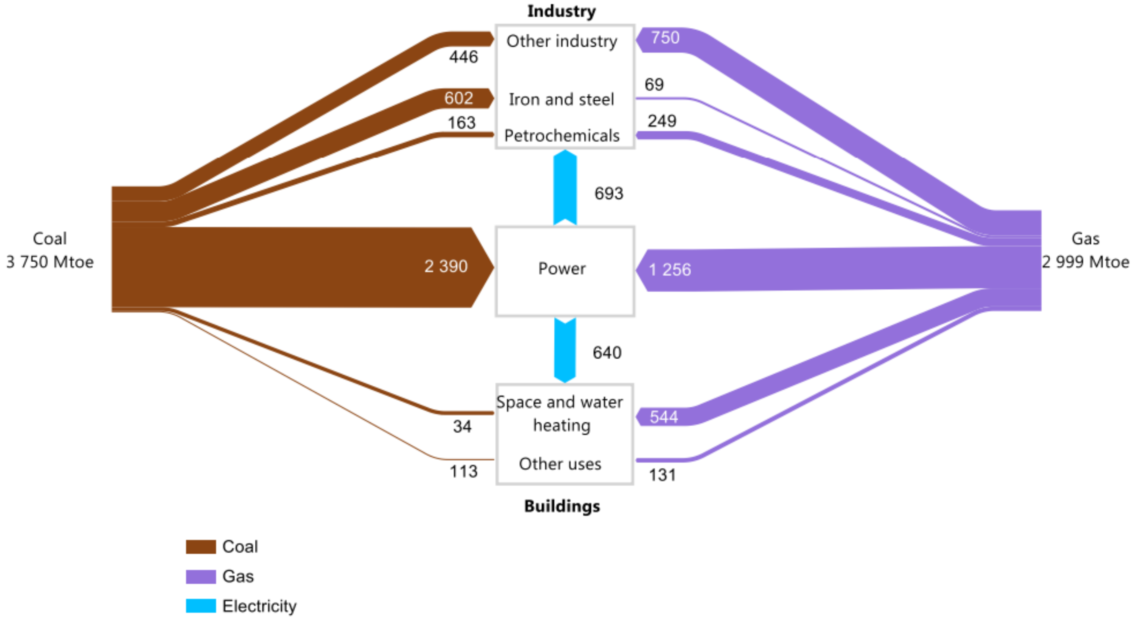
The primary transition has been in the power sector, where the increased utilization of natural gas has noticeably reduced CO_2 emissions. The IEA reports that existing power infrastructure in the U.S. still holds considerable potential for further coal-to-gas conversions, although this potential is highly contingent on the age of the coal plants and, to some degree, the wide fluctuations in natural gas prices. Its analysis concludes that additional fuel switching from coal to natural gas generation could curtail up to 1.2 gigatons of CO_2 emissions in the near term, provided that relative prices and regulatory support are in place.

In the U.S., coal-to-gas switching was responsible for nearly 20% of the total emissions reductions in the United States between 2010 and 2018.[64] In the EU, since 2010, high natural gas prices and low CO_2 prices have discouraged substantial coal-to-gas switching in most European Union countries. Introducing a carbon price floor in the EU has, however, hastened the phase-out of coal-fired power plants. In addition, as CO_2 prices continue to rise, the economic viability of switching from coal to gas in the EU's power sector is improving, and the ongoing coal phase-out may offer short-term opportunities for natural gas. These opportunities will depend on natural gas prices and availability, the evolution of renewable alternatives, and the development of battery technologies to provide flexible low-carbon energy that can meet demand peaks. Natural gas compared to coal generation emits about 50% less CO_2 and when using gas for heating, emissions decrease by 33%.[65]

Coal to gas fuel switching also could reduce industrial sector emissions, especially in subsectors the use significant amounts of electricity in their manufacturing processes. As seen earlier in Figure 5 for example, electricity is around 45% of the energy shares used for making aluminum, creating significant opportunity for coal to gas fuel switching. Also in Figure

24, which depicts global coal and natural gas flows and associated uses of electricity, the iron and steel industries used 602 mtoe of coal in 2017, compared to 69 mtoe of natural gas.

Figure 24. Selected flows of coal and gas in the global energy balance, 2017, IEA



Note: *Industry* includes other energy sector and other non-energy use. Figure excludes gas and coal use in the transport sector.

Note:

Mtoe = million tons of oil equivalent

Source: IEA (2019b), The Role of Gas in Today's Energy Transitions

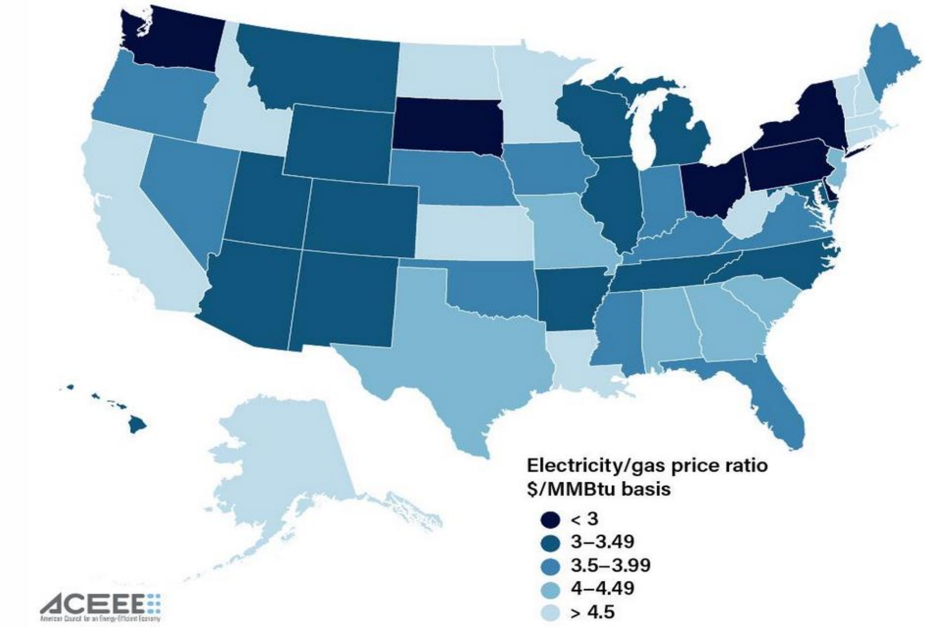
Transitioning from coal to natural gas in the power and industrial sectors offers substantial opportunities for reducing CO_2 emissions in the short term. In addition to opportunities in iron and steel, Fig. 25 also highlights the potential for emissions reductions from coal to gas fuel switching for a range of uses. This switching can serve as a valuable intermediate step to decrease the carbon footprint while more advanced technologies and carbon capture and storage (CCS) solutions are developed to further decrease the carbon footprint of the industry. However, the goal should be shifting to electrification or low-carbon gas sources to achieve long-term sustainability and further minimize greenhouse gas emissions, ensuring a more environmentally friendly energy landscape in the future.

5.3. Industrial Heat Pumps

Analysis by the American Council for an Energy Efficient Economy (ACEEE), concludes that industrial heat pumps (IHPs) could provide up to 160 ° C, replacing fuels currently used to meet about 30% of process heat needs, and would be especially beneficial to the food and beverage, pulp and paper, and chemicals industries.[66] This analysis notes that IHP technologies could:

- Save the equivalent energy use/year of 2.7–3.1 million homes (26–32% of the source energy [net, after subtracting electricity use] depending on the scenario);
- avoid emissions equivalent to those of 6.5–9.4 million cars/year (30–43 million metric tons CO_2e /year in 2022); and
- use 5 gigawatt/year of additional electricity to run the IHPs, facilitating electrification. A gigawatt is the amount of electricity needed to run a medium sized city."

Figure 25. Electricity to gas price ratio in the US



Source: ACEEE

This ACEEE analysis also acknowledges the significant regional price differences between electricity and natural gas (Figure 25). Because of the significant price differential in many regions of the country, e.g., over 4. 5 times greater in California, to realize the full environmental potential and value of this technology, ACEEE recommends, "support for pilots, enabling policies, and development of infrastructure that will increase access to and reliable use of beneficial electrification for industry." This analysis underscores several key points: low temperature process heat can be electrified; there are available technologies for doing so; these technologies could add costs to industrial processes, raising issues of competitiveness in global markets and affordability for consumers; and the need for policies to accelerate the deployment of these technologies to address the urgency of climate change.

Innovation is also needed to develop technologies for electrifying heat that are in the development or pilot phase, particularly those designed for high-temperature industrial processes. Additional investment in research and development is also essential, specifically addressing the challenges associated with high-temperature heating processes commonly employed in cement, glass, and specific chemical production industries.[67]

5.4. Carbon Capture and Storage

Carbon capture and storage (CCS) is a process intended to capture anthropogenic CO_2 at its source and store it to avoid its release into the atmosphere. CCS could reduce the amount of CO_2 emitted to the atmosphere from power plants and other large industrial facilities.

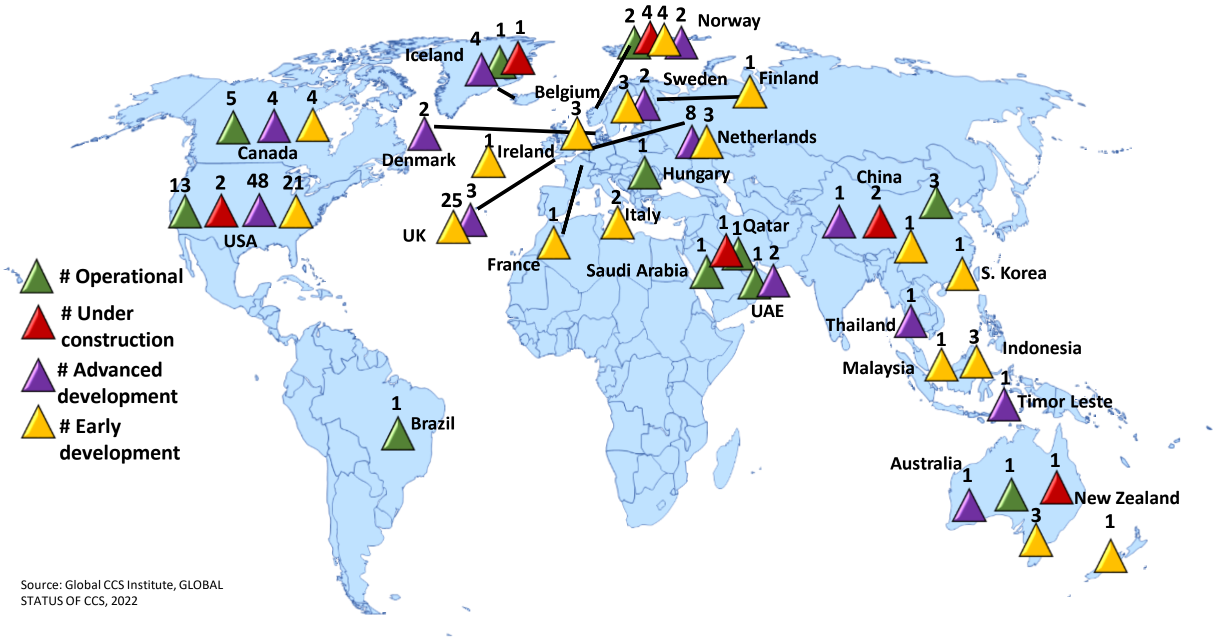
An integrated CCS system includes three main steps: (1) capturing and separating CO_2 from other gases; (2) compressing and transporting the captured CO_2 to the sequestration site; and (3) injecting the CO_2 into subsurface geological reservoirs for storage. The most technologically challenging and costly step in the process is the first step, carbon capture. Carbon capture equipment is capital-intensive to build and energy-intensive to operate, representing up to 75% of the project cost in some cases.[68]

Carbon Capture and Sequestration (CCS) is a critical technology that can capture more than 90% of CO_2 emissions from power plants and industrial facilities. Captured carbon dioxide can be stored in underground geologic formations or used in the manufacturing of fuels, building materials, enhanced oil recovery, and more. CCS is a mature technology that is ready to be deployed at scale. Thirty commercial-scale carbon management projects are operating around the world with 11 more under construction and 153 in different stages of development. Overall, large-scale carbon management can achieve 14% of the global greenhouse gas emissions reductions needed by 2050 and is viewed as a pragmatic solution to achieve deep decarbonization in the industrial sector while alternatives are developed.[69]

Evaluations by the Intergovernmental Panel on Climate Change (IPCC), suggest the need to scale up carbon removal efforts to approximately seven gigatons (Gt) of CO_2 annually by the middle of this century.[70] Carbon removal solutions encompass a range of innovative technologies and practices designed to mitigate the impacts of climate change. These include reforestation, soil carbon storage, and direct air carbon capture and storage (DACCS). Similarly, the IEA's 2020 Sustainable Development Scenario shows CCS providing nine percent of emissions reductions by 2050 and noted that "Reaching net zero will be virtually impossible without CCS". Figure 26 shows CCUS projects in countries around the world at various stages of development in 2022.

Between 2019 and 2022, operating projects increase by 58%. In that same period, projects in advanced development increased by 670%, indicators of a strong interest in and need for CCS projects.[71] *Operating projects in 2022* included four for fertilizer production, four for ethanol production, 13 for gas processing, one for refining, one for chemical production, and one for power generation. *Projects in advanced development in 2022* included, among others, 32 for ethanol production, seven for hydrogen production, five for gas processing, two for chemical production, two for chemical production, one for refining, and 12 for power generation.

Figure 26. Country Locations of CCUS Projects at Various Stages of Development, 2022



Source: Global CCS Institute, GLOBAL STATUS OF CCS, 2022

Importantly, CCS use at natural gas power plants can reduce associated carbon emissions by 90%.[72] The process can also be applied to natural gas treating and processing facilities, where the natural gas from producing wells is treated to remove nonhydrocarbon products. During the treatment process, CO_2 and other gases are released to the atmosphere by flaring and venting.

Challenges with CCS deployment include the high cost of retrofits and associated infrastructure, such as pipelines. Compared to natural gas and hazardous liquid pipelines, the construction and operation of CO_2 pipelines is less risky, however, public opposition to pipeline development, regardless of the pipe's intended use, is also a significant risk. In addition, permitting CO_2 pipelines and wells, used for the sequestration of captured CO_2, is also a challenge due to long permitting times which may not align with decarbonization timelines. Finally, without a price on carbon, the CCS industry will struggle as an option.

In the United States., existing systems already capture gases to inject them into Acid Gas Injection (AGI) wells in the case where hydrogen sulfide (H_2S) is also present in the waste stream. The Environmental Protection Agency (EPA) regulates the drilling and use of AGI wells through the Underground Injection Control (UIC) Program. Recent 45Q tax credits have been expanded to accelerate CCS project development and deployment. This focus on CCS from industrial sources could help meet national and global climate change mitigation goals.

Box 2

CarbonSAFE: An Example of U.S. R&D in CCS/CCUS

In addition to tax incentives, in the United States, the U.S. Department of Energy develops research and development on CCS/CCUS through funding from programs such as the Carbon Storage Assurance Facility Enterprise CarbonSAFE initiative. The initiative is a research and development program aimed at advancing the development of geologic storage sites for the secure and long-term storage of CO_2 captured from industrial sources and is focused on developing geologic storage sites for safely storing over 50 MMT of CO_2 captured from industrial sources. These projects aim to enhance our understanding of project screening, site selection, characterization, monitoring, verification, accounting (MVA), and assessment procedures. They also provide the necessary information for permits, injection strategies, and monitoring plans for large-scale CO_2 storage projects.

The current research within the CarbonSAFE Initiative involves onshore field projects that address various technical and non-technical challenges specific to large-scale CO_2 storage. This includes forming capable project teams, developing comprehensive plans covering technical, economic, and public acceptance aspects, and conducting high-level technical assessments of the storage site and potential CO_2 sources. Additionally, feasibility studies focus on specific reservoirs within the storage complex, involving data collection, geologic analysis, regulatory compliance, subsurface modeling, risk assessment, monitoring planning, and public engagement.

The initiative plays a crucial role in advancing CCS technology in the United States by addressing technical, economic, and regulatory challenges associated with large-scale CO_2 storage. It supports efforts to reduce carbon emissions from industrial sources and could help the U.S. and the world meet net zero targets.

5.5. Hydrogen

Hydrogen is a possible substitute for natural gas and coal use for achieving the high levels of heat needed for key industrial processes. Hydrogen shares several key characteristics with natural gas. It possesses qualities like transportability, storability, and high energy density. a notable advantage of hydrogen is its capacity to combust without directly emitting pollutants or greenhouse gases.[73]

At present, in nascent market development stages for use as an energy commodity, hydrogen is not yet available in volumes sufficient to meet large scale supply or demand needs and its costs are high, which could impact the competitiveness of industrial products. Also, natural gas infrastructure is not fully compatible with hydrogen so potential retrofits would add to the cost and price.

Shifting from natural gas to low-carbon gas alternatives, including hydrogen, represents a significant strategic move in the broader goal of decarbonizing energy, industry, and transportation sectors. However, its adoption is particularly crucial in sectors where hydrogen is currently underutilized, and the requisite infrastructure does not yet exist to support transportation, heating and cooling, and power generation[74]. Hydrogen could replace natural gas as a thermal source in industrial applications, such as steel production, ammonia production, and chemical manufacturing. It could also be used for residential and commercial heating, but adjustments to appliances and rebuilt distribution systems would be necessary. When comparing the additional cost of CCS to make blue hydrogen, it will be weighed against the cost to produce use green hydrogen, produced from renewables.

A color-coding system has been established to categorize the technologies used in hydrogen production. The primary color designations associated with hydrogen production methods are green, blue, and grey. "Green hydrogen" is generated using renewable energy sources through electrolysis, resulting in zero carbon emissions from the production process. "Blue hydrogen" is produced from natural gas via steam methane reforming; emissions from this process are captured and stored, making it a low carbon fuel. Conversely, "grey hydrogen," which is the most prevalent form of hydrogen production currently, is derived from natural gas, specifically methane, via steam methane reformation, without capturing the greenhouse gases produced during this process.[75] It is important to note that all forms of hydrogen production require clean water resources which may already be strained in areas where development is desired. Most of the hydrogen currently produced in the U.S. is made from unabated natural gas (grey hydrogen).

According to the IEA, around 75 Mt per year of pure hydrogen is produced and around 76% is from natural gas. This combined with coal-based hydrogen production resulted in emissions of roughly 830 $MtCO_2$ per year in 2016/17, or 4.7% of global industrial direct and indirect emissions.[76] In addition, a significant portion of the energy content of methane (30%) is lost in the conversion to hydrogen, and energy used for hydrolysis becomes otherwise unavailable to meet increasing energy demands.

Transitioning to low-carbon or zero-carbon hydrogen from natural gas will be complex and require careful planning, technological innovation, strong policy support, significant infrastructure, and an increase on cost of more than 30% over directly using natural gas. In discussing industrial decarbonization, it is important to consider the unique characteristics of hydrogen as an energy carrier and to address challenges related to infrastructure, cost, safety, and scalability.[77]

Pipelines are the most cost-effective way to transport significant volumes of hydrogen. However, some companies worry about the lack of clarity in existing regulations of hydrogen pipeline infrastructure. This, in turn, has made investors hesitant to invest in hydrogen pipelines, especially because future hydrogen demand is uncertain. Importantly, hydrogen embrittles pipelines; above certain levels of blending, pipelines would require special treatment to transport pure hydrogen.

Blending hydrogen with natural gas in existing pipelines could enable an infrastructure to support additional hydrogen demand, as well as reduce emissions depending on the method of hydrogen production. Existing natural gas pipelines and end users can handle a partial mix of hydrogen without major infrastructure changes or safety issues.[78] Blending hydrogen in these pipelines creates near-term demand for hydrogen and if blue or green hydrogen is used, could reduce the carbon intensity of end uses, while satisfying the ongoing need for a fuel for industrial processes. This potential has caught the attention of both private and public sectors. The following challenges need to be addressed to develop a hydrogen economy.

(1) The infrastructure needed to develop hydrogen as an energy commodity as opposed to a specialty chemical. Some existing natural gas pipelines can potentially be repurposed to transport hydrogen, but modifications would be needed as hydrogen requires different metallurgy than much of the existing natural gas infrastructure.

(2) Hydrogen storage solutions need to be developed to ensure adequate and reliable supplies (for example to balance the intermittent nature of renewable energy sources used to produce green hydrogen).[79]

(3) In terms of cost and needed investments, green hydrogen is currently more expensive to produce compared to SMR, but costs could decrease as renewable energy becomes more affordable, though this would require faster growth in renewables than are currently projected through 2050. Also, transitioning to hydrogen requires substantial investments in production facilities, pipelines, and storage infrastructure.[80]

(4) Hydrogen has different safety characteristics and transportation pressure profiles than natural gas, so safety standards and regulations need to be adapted.

5.5.1. Feedstock for Hydrogen and Backup Renewable Power

Natural gas is used as a feedstock to produce hydrogen. Currently, most hydrogen is made from steam methane reforming of natural gas (SMR). Reforming low-cost natural gas can provide hydrogen today for hydrogen fuel cells as well as other applications, though at an increase in gas demand of 142% due to loss of energy used to perform the conversion to receive the same net power. Over the long term, it is expected that hydrogen production from natural gas will be augmented with production from renewable, nuclear, natural gas with carbon capture and storage, and other low-carbon energy resources.

In addition, natural gas-fired power capacity could play an increasingly important role in providing backup to growing supplies of intermittent renewable energy, in the absence of a breakthrough that provides affordable utility-scale storage.[81]

5.6. Efficiency Options

According to the U.S. Department of Energy's “Industrial Decarbonization Roadmap,” energy efficiency is one of four key pillars for decarbonizing the sector. It is a foundational, crosscutting decarbonization strategy and is the most cost-effective option for greenhouse gas emission reductions in the near term. Energy efficiency efforts include:

- Strategic energy management (SEM) approaches to optimize the performance of industrial processes at the system level,
- Systems management and optimization of thermal heat from manufacturing process heating, boiler, and combined heat and power sources, and
- Smart manufacturing and advanced data analytics to increase energy productivity in manufacturing processes.

Economics is the principal driver for industry; the largest incentive for increased energy efficiency is to lower total operating costs. Fortunately, the opportunities for increased efficiency are numerous and substantial. Independent studies[82] indicate that U.S. industry could reduce energy use by 14% to 22% in the near term through cost-effective efficiency measures—particularly existing technologies that make use of the heat produced in power generation.

5.6.1. Application of Best Available Technologies

Increasing the energy efficiency of production processes is the most cost effective, near-term solution to reducing GHG emissions from the industrial sector. Energy efficiency improvements from fuel switching can entail radical technological changes, which makes them uneconomic solutions. Energy efficiency can be achieved through two channels: strategic energy management (SEM) approaches and energy-saving best available technologies (BATs) at industrial facilities (IPCC 2022). For example, a case study of 3M and Schneider Electric's SEM practices showed that sites that implemented such practices demonstrated energy performance improvements[83] that were up to 65% greater than sites without formal energy management systems.[84] Additional research also shows the effect of adopting SEM on a plant's efficiency, including a 6.4% realized energy savings after appointing an energy manager and 6.9% realized energy savings after undertaking an energy audit, with these values likely representing a lower bound.[85] The U.S. Department of Energy (DOE) recently highlighted the energy efficiency progress made by its more than 250 manufacturing partners in its 2021 Better Plants Annual Progress Update report. These organizations, which make up roughly 13.8% of the U.S. manufacturing energy footprint, have cumulatively saved $9.3 billion and 1.9 quadrillion British thermal units (Btu) of energy since inception of the program. Their annual energy intensity improvement rate is reported to be 2%.[86]

5.6.2. Combined Heat and Power

Industrial combined heat and power (CHP) technology has long been used by industry to provide reliable heat and power with high efficiency and lower emissions. The energy savings and GHG emissions reductions benefits of CHP are found in the aggregate reduction in overall energy consumption: CHP replaces both a separate onsite thermal system (furnace or boiler) and purchased power with a single, integrated system, efficiently producing both thermal energy and electricity at the point of use. Industrial CHP systems, through both topping and bottoming cycles, can provide needed energy services for some subsectors with overall energy efficiencies of 65%–85% compared to separate production of heat and power, which collectively averages 45%–55% system efficiency.[87] In particular, CHP is prevalent in chemicals, pulp and paper, refining, primary metals, and food industries, but can also be found in crop production, nonmetallic minerals, and other uses.[88]

Industrial CHP can provide significant GHG emissions reductions in the near- to mid-term as marginal grid emissions continue to be based on a mix of fossil fuels in most areas of the country. In order to prevent lock-in, CHP units installed today must have emissions below marginal grid emissions for the duration of their useful lifetime, including through retrofits to use clean sources of energy where possible.

Converting some natural gas infrastructure over time to renewable natural gas (RNG), synthetic natural gas or hydrogen produced from nuclear energy, and hydrogen is one strategy to decarbonize CHP. Engine and gas turbine manufacturers are currently testing and operating CHP systems on high percentage hydrogen fuels in preparation for increasing use of RNG and hydrogen in the future. RNG and hydrogen fueled CHP systems can be a long-term path to decarbonizing industrial thermal processes resistant to electrification because of technology or cost barriers, and for critical operations where dispatchable onsite power is needed for resilience and reliability.

5.6.3. Digitalization

A key method to improve energy efficiency is through digitalization. Smart manufacturing and advanced data analytics could help the manufacturing sector unlock energy efficiency from the equipment level to the entire manufacturing facility and the whole supply chain. These technologies could make manufacturing industries more competitive, with intelligent communication systems, real-time energy savings, and increased energy productivity. A sophisticated energy impacts analysis and associated data and tools are needed to quantify energy and economic impacts on national, industry sector, facility, energy system and equipment levels.[89] RD&D is needed to better understand the cost of cyber-physical systems for different manufacturing plants and subsectors, including the cost of sensors, controllers, smart equipment, and information and communications technology (ICT) equipment.

Yet the potential for digital technologies to reduce emissions through increased efficiency is higher in non-energy-intensive sectors and generally limited in energy-intensive sectors (IPCC 2022). This is a challenge for reducing emission through efficiency measures as the generation and use of heat (e.g., process heating, boilers, and combined heat and power [CHP] systems) is the most significant end use of energy in the industrial sector (by a significant margin), followed by machine-driven systems.[90] The proportion of energy used for process heating varies by industry across broad ranges with the lower temperature ranges (below 150°C) offering the most significant energy reduction opportunities for current and emerging technologies, in large part due to its ability to be electrified.[91]

Significant investments in digital solutions are being carried out in most industrial sectors, also because of public commitment to promote the transition toward Industry 4.0[i].[92] Investments in energy efficiency technology development should be informed by the broad context of energy transitions underway in the world, particularly when large capital investments are involved that might lock-in that technology over long periods. For example, an energy-efficient process heating system that relies on fossil fuel combustion may improve energy efficiency in the short term— but as electric grids transition to clean energy, electrified technologies may provide a greater emissions reduction in the long run. Careful consideration of such tradeoffs will be critical to a pragmatic and sequenced decarbonization approach.

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[i] Industry 4.0 refers to the fourth industrial revolution due to major advancement and diffusion of digital technologies (European Parliament 2015).

6. Case Studies

The following are two case studies, the first on glass manufacturing in France and the second cement and steel production in the United States. These case studies highlight the opportunities and restrictions in decarbonizing industry.

6.1. Case Study 1: Decarbonization of Glass Manufacturing

Glass is a versatile material with many uses across various industries and in everyday life. Glass manufacturing plays a significant role in the industrial landscape, contributing to various sectors of the economy and serves as a critical component in many industries.

Industrial glass manufacturing is a complex process that transforms raw materials into useful products that are used in numerous daily applications. With its unique combination of transparency, strength, and versatility, glass plays a vital role in modern society, from windows in our homes to the screens for smartphones, to the bottles for food and beverages. Its manufacturing process involves the fusion of various raw materials, such as silica, limestone, and soda ash, at extremely high temperatures to create a molten glass mixture. Once formed, this molten glass is carefully shaped, cooled, and processed to produce an array of products that range from flat sheets and containers to intricate optical lenses and high-tech electronics components.

Environmental concerns have, however, played a pivotal role in shaping glass market dynamics. Glass manufacturing is energy intensive and a significant source of GHGs emissions. Both the fuels and the processing of raw materials used in glass manufacturing emit CO_2 when heated in glass melting furnaces.

6.1.1. Glass market size and growth

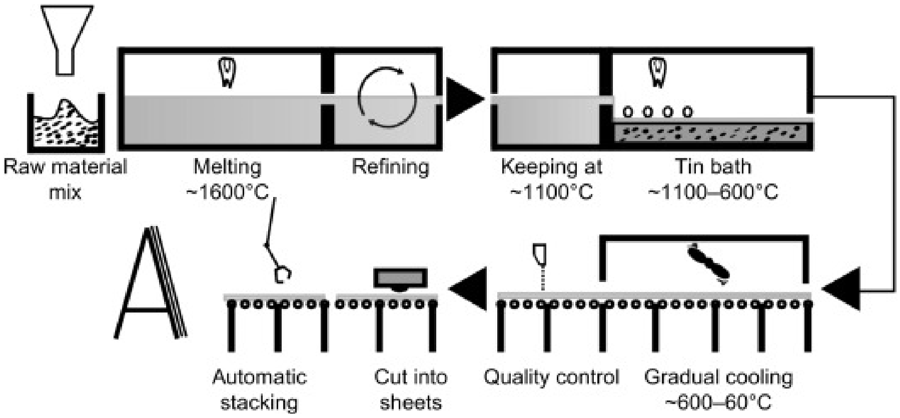
As of 2022, the global glass manufacturing market was valued at around $265 billion and is projected to experience substantial growth, possibly reaching a value of approximately $400 billion by 2030.[93] One of the primary drivers of this growth is the soaring demand for consumer electronics. This trend is driven, in part, by the proliferation of smartphones and a gradual decline in the prices of electronic devices.

Also, an extensive surge in infrastructure development and construction activities is expected to boost the demand for glass in the foreseeable future. The industry's demand is closely tied to sectors such as construction and automotive, with growing populations, urbanization trends, and rising incomes in emerging economies further influencing the demand for glass products. These combined factors have contributed significantly to the glass market's expansion.

6.1.2. Glass Manufacturing Processes and Energy Sources

The production process of glass can be divided into four main steps. First, in the batch preparation and mixing stage, raw materials, including silica, limestone, soda ash, borosilicate, additives, and recycled glass, are blended, ground, and mixed before entering the melting furnace. These prepared materials are then added to glass melting furnaces of various sizes and designs in the melting, refining, and conditioning phases. The required temperatures can range from 600ºC to 1600ºC (Fig. 28). The resulting melted glass is refined to remove bubbles, homogenized, and heat conditioned. Regulating glass temperature ensures that the glass is at the optimal temperature for forming and shaping. The third step – forming – involves shaping the refined glass into the desired product. Finally, in the finishing stage, the formed glass is subjected to processes designed to meet specific product characteristics.[94] As seen in Figure 28, the float glass process – making sheets of glass – requires a substantial amount of heat, resulting in significant energy consumption. Glass melting represents 87% of energy consumption for flat glass and around 80% for other types of glass.[95]

Figure 28. Overview of Float Glass Process



Source: Float Glass Process – an overview, Achintha. https://www.sciencedirect.com/topics/engineering/float-glass-process

Heat and power are critical for the glass industry. The glass manufacturing industry typically uses a combination of energy sources to meet its high temperature requirements and power the various processes involved in its production. The use of coal in glass production has been driven by access to and affordability of alternative energy sources. Coal has historically been used in glass manufacturing for its high heat generation capabilities. However, coal use has decreased in recent years due to environmental concerns and a shift toward cleaner energy sources, including natural gas.

Modern glass manufacturing facilities often incorporate heat recovery systems to improve energy efficiency. While natural gas combustion generates a considerable amount of waste heat, it can be captured and reused by the facility for various purposes, including preheating raw materials, heating incoming combustion air, or providing heat for other industrial processes.

In the industrial sector, over the lifespan of the equipment, the fuel costs are over ten times greater than the initial capital investment in the equipment. In medium- and high-temperature heat applications, electric furnaces require a comparable capital investment and exhibit similar efficiency levels as their conventional counterparts. Therefore, the investment required to transition to electric equipment relies on the difference between the ongoing energy operational costs for electric furnaces and those for conventional fuel-base.[96] As such, the electricity to natural gas price ratios seen in Figure 26 are highly relevant and could impact the overall cost and price of the glass and, at a minimum need to be compared to the costs of making gals with conventional furnaces and fuel with carbon capture and sequestration.

As noted, the use of natural gas as an energy source in the glass manufacturing industry is significant. It is favored for its high energy density and clean-burning properties, making it suitable for high-temperature processes. Natural gas is primarily used for two critical processes for making glass: melting raw materials and providing heat for temperature control during various stages of glass production. This is crucial for producing glass with specific properties and for ensuring that the glass remains in a workable state as it moves through the manufacturing process.

Electricity is used at various stages in glass manufacturing, including for powering equipment, conveyors, and lighting. The primary advantage of electric melting compared to fossil-fueled melting lies in its higher efficiency. In addition, electric melting furnaces potentially have lower investment costs due to their smaller furnace volumes, the absence of regenerators, and the elimination of expensive high-temperature crowns. They also significantly reduce combustion-induced gaseous emissions like CO_2, NO_x, and dust, reducing the need for costly filter systems.

However, drawbacks include low volume capacity, dependence on electricity prices that can be high in some regions relative to natural gas prices and the necessity to have a reliant electric grid. Also, the high heat requirements for making glass limit the value of electricity in the glass-making process, as electricity can typically produce heat at a maximum temperature of about 400°C. These factors show both the technical and economic limitations of the use of electricity for many glass products.

Industrial decarbonization and the desire, or necessity, for manufacturers to sell low-carbon or net-zero carbon products has many industries looking for alternative processes. Reducing glass plant GHG emissions and product carbon intensity are important goals for both the glass industry and its customers. The industry continues to explore energy-efficient and sustainable alternatives as part of their long-term environmental and economic strategies.

Decarbonization strategies currently include enhancing recycling and energy savings (waste heat recovery) but could include CCS in the future, if industry is appropriately incentivized to do so. Substituting fossil fuels with biogas or hydrogen, electrifying large-capacity furnaces, and implementing carbon capture represent more techno-economic challenges even though all are viable solutions for reducing carbon emissions in the glass industry. For example, biogas will generate additional costs and the source and availability of biogas pose challenges (in 2016, the glass industry consumed 10 TWh, while only 0.2 TWh of biomethane were injected into the grid). The use of hydrogen will require furnace replacements, current furnaces are only capable of replacing 20% of natural gas with hydrogen due to differences in thermal and radiative properties.[97]

Glass manufacturers will, however, continue to focus on total costs when making technology and investment choices. In an era of rising renewable energy adoption, energy efficiency and operational adaptability will gain greater significance, accompanied by an increased emphasis on energy security. Simultaneously, the decarbonization solutions chosen must possess the necessary technological maturity, and technical considerations such as glass quality, coupled with country-specific regulations; the considerations will significantly impact the decision-making process for specific glass production methods.[98]

6.1.3. Glass in France and the Clean Energy Transition

This case study briefly examines the glass industrial sector evolution in France and the effect the decarbonization efforts have on the industry. France is the second-largest glass producer in Europe, with an annual output of approximately 4.6 million tons Importantly, in France, the thermal energy necessary for glass fusion comes mainly from natural gas (85%) and only 10% from electricity.[99]

In France, the glass industry is vital not only for its contributions to economic growth and technological advancements but also for its role in environmental sustainability. Glass contributes to energy-efficient buildings, renewable energy solutions like photovoltaic panels, and sustainable packaging. The global glass manufacturing market is experiencing significant growth, driven by factors like the demand for consumer electronics, infrastructure development, and increasing environmental awareness.

French architectural designs frequently integrate advanced glass solutions to elevate a buildings' visual appeal and optimize its energy efficiency. Glass walls capture and retain warmth during winter while effectively shielding interiors from excessive solar heat during the summer. Using low-emissivity coatings (known as Low-E) on windows plays a pivotal role by directing infrared light back into the indoor spaces, thus maintaining a consistent temperature environment throughout all seasons. Finally, providing more natural light in buildings reduces the electricity needed for lightning.[100]These characteristics significantly diminish the requirement for supplementary heating or cooling mechanisms, leading to a notable reduction in overall energy consumption.

In addition, in France, glass packaging is very important. Glass packaging is prized for its ability to maintain product quality and its recyclability, aligning with sustainability goals.

Indeed, glass is a sustainable packaging material as it is infinitely recyclable without losing quality. As in much of the rest of the world, the food, beverage, and luxury industries in France rely on glass containers for packaging a wide range of products, including wine, champagne, perfume, and various gourmet goods. France relies heavily on the beverage market (accounting for 79% of glass packaging); exports of its wines and spirits has the second largest surplus in the French trade balance.

Environmental concerns are leading to the preference for eco-friendly materials like glass. The French government is targeting a reduction of greenhouse gas emissions of 50% by 2030 from a 1990 baseline and in France, glass plays a significant role in the clean energy transition. According to the French Glass Federation, glass production in France resulted in 2.7 million metric tons of CO_2 equivalent emissions, constituting 0.6% of the nation's total emissions and 3.3% of emissions from the French industrial sector. Approximately 20% of these emissions can be attributed to the use of raw materials, while the remaining 80% is attributed to the utilization of fossil fuels. Importantly, in 2019, the EU's Emissions Trading System (ETS) allowances covered 85% of declared emissions from the French glass industry. In the absence of these quotas, glass production costs could rise by approximately 5% with a cost of €25 ($26.67) per metric ton of CO_2.[101]

Consequently, the glass industry in France is embracing sustainability, with a focus on reducing energy consumption and carbon emissions from its manufacturing. These and other market demand and policies in France are compelling glass manufacturers to pursue decarbonization efforts within their industry, a complicated task given the high energy intensity inherent to glass manufacturing processes. The sector is actively engaged in eco-design and reducing packaging weight. Also, the perfumes and cosmetics industries are also driving glass suppliers to limit their environmental footprint.

At the same time, France's commitment to renewable energy sources has also led to increased demand for specialized glass products. Glass manufacturing in France, for example, plays a role in the production of various high-tech and energy-related products, such as photovoltaic solar panels, optical lenses, and specialty glass used in electronics manufacturing.

Electrification of high-capacity furnaces is an important – but not yet fully developed or deployed -- technology for furnaces exceeding a daily capacity of 200 tons. To develop the technology, the European Container Glass Federation launched an initiative called the *Furnace of the Future*.[j]The European project gather major packaging glass manufacturers that aims to achieve a 50% reduction in CO_2 emissions and the development of a high-capacity hybrid furnace.[102]

In this context, in 2019, approximately half of France's total energy supply was domestically generated and 79% of this generation was zero emissions nuclear power. France's operating of nuclear power plants for extended periods while adhering to strict safety standards

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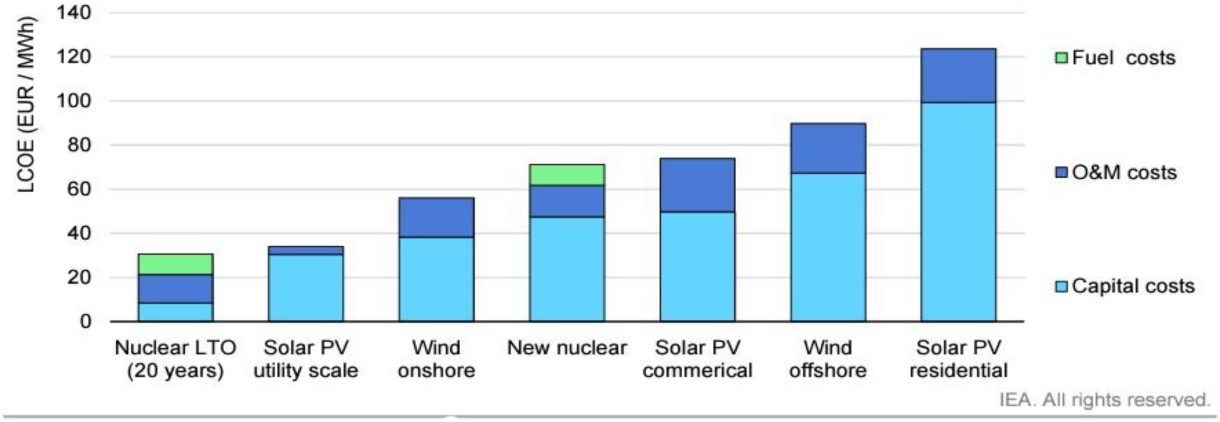
[j] *Furnace for the Future* is a European glass industry project that fosters electric melting technology that will allow the switch to renewable electricity and dramatically reduce CO_2 emissions.

represents an economically efficient approach to generating environmentally friendly, low-carbon electricity. According to the 2020 edition of the IEA/NEA publication titled "Projected Costs of Electricity," France is projected to incur costs of approximately$30 per megawatt-hour (MWh) for maintaining these plants in operation for either a minimum of 10 or 20 years (Figure 29).[103]

Nuclear generation gives France an advantage for electrification of its industry, where electricity costs for nuclear generation are competitive with natural gas and where industrial processes do not require high levels of heat. Nuclear power in France however faces several challenges including uranium supply risks, public perception of nuclear power, and the age of its existing nuclear plants.

Figure 29. Projections for the levelized cost of electricity in France by technology



Notes: LCOE = levelised cost of electricity. MWh = megawatt hour. O&M = operating and maintenance. LTO = long term operation. PV = photovoltaic. Data are based on a 7% discount rate and costs are projected for the year 2025 based on data submitted by the Ministry of the Ecological Transition.

Source: IEA, Projected Costs of Generating Electricity 2020

In summary, in France, policies for glass manufacturing and its uses contribute to economic growth, technological advancements, and environmental sustainability, as well as to mitigating some of its greenhouse gas emissions to help France to meet its climate goals. The versatility and adaptability of glass make it a critical material for a wide range of applications, aligning with the diverse needs of French industry and its climate objectives. French glass manufacturers contribute to the country's sustainability efforts by producing eco-friendly packaging solutions and promoting recycling initiatives. France is well positioned for electrification of many of the steps in the glass making processes as 79% of its domestic electricity generation is zero emissions nuclear power.

6.1.4. Case Study Summary

In conclusion, the decarbonization of industries such as glass manufacturing that are energy-intensive and require high-heat as glass manufacturing (or cement and steel) face numerous challenges and opportunities. These industries' high energy demand, primarily met by fossil fuels, has made them major contributors to greenhouse gas emissions from hard-to-abate sectors. To align with sustainability goals and meet the demands of environmentally conscious consumers and clients, glass manufacturers are actively pursuing decarbonization strategies.

However, the glass manufacturing process is energy-intensive, with a substantial portion of energy used for high-temperature processes. While natural gas has been the primary energy source for making glass, electricity is emerging as an alternative, albeit a limited replacement option. Electricity offers higher efficiency and lower GHG emissions, but other than arc furnaces for making steel, is generally limited to lower temperature processes, requires additional furnace capacity, and remains expensive. Initiatives like the *Furnace of the Future* seek to overcome these challenges and advance electrification technologies.

Addressing the critical challenges in the sector involves decarbonizing energy inputs for glass production and reducing emissions related to raw materials. Europe is actively exploring technologies like hydrogen, biomass, and decarbonized electricity as energy sources for glass production, but these options come with significant infrastructure and investment challenges and costs, underscoring the importance of long-term planning and thoughtful, sequenced policies. In this evolving landscape, life cycle assessments, methodologies for accurately quantifying Scope One, Two and Three emissions, and utility data analysis will be instrumental in guiding decisions and strategies for achieving a more sustainable and environmentally friendly future for the glass industry.

The decision-making process for energy sources in the glass industry involves several factors, including cost-efficiency, availability, and environmental impact. In France, the operation of nuclear power plants has made low-carbon electricity readily available. However, challenges such as uranium supply risks, public perception of nuclear energy, and aging power plants must also be addressed. In other countries, industrial decarbonization for the glass industry also faces cost pressures associated with natural gas competitiveness relative to other energy sources.

6.2. Case Study 2 – Hard to Abate Sectors – Cement and Steel

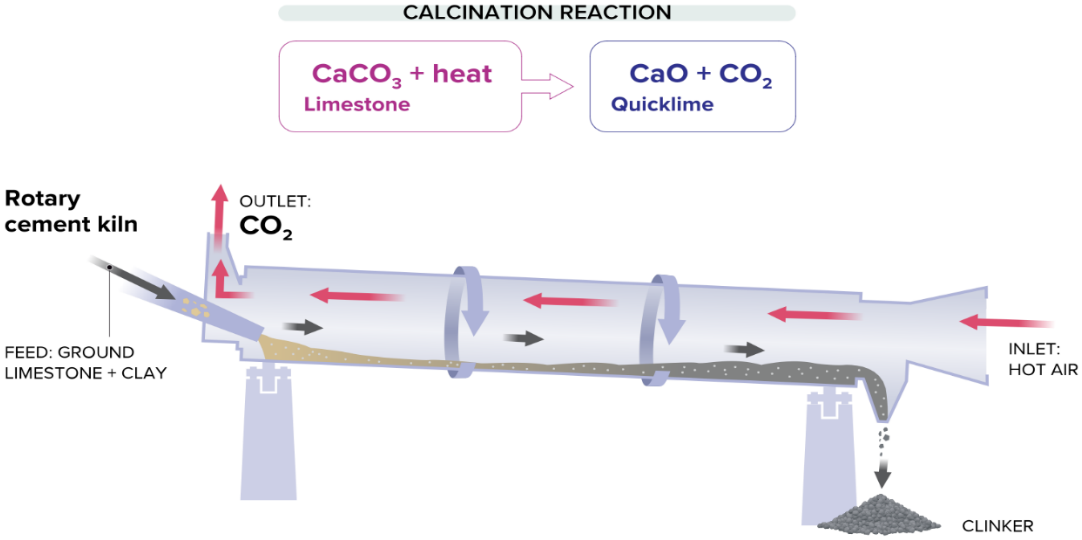
Industrial sub-sectors, particularly the cement and steel industries, play a pivotal role in the global economy, providing essential materials for construction, infrastructure, and manufacturing. However, they are also among the largest contributors to hard-to-abate carbon dioxide (CO2) emissions, which pose significant challenges in achieving global, regional and national climate goals. Iron and steel production is one of the highest-emitting industries, accounting for around eight percent of global CO2 emissions, cement accounts for around seven percent.[104]

These emissions are considered "hard-to-abate" because mitigation measures like electrification from low carbon generation sources is insufficient or inadequate for production of the materials. Both concrete and steel production are inherently energy-intensive processes; the use of raw materials and the processes for their use in manufacturing requires extremely high temperatures, the generation of which generally relies on fossil fuels. But most importantly because the production of concrete and steel involves chemical reactions that release carbon dioxide as a byproduct, they remain hard to abate sectors. To achieve a low-carbon future, mitigating these emissions will be essential.

The concrete industry is fundamental to construction, and concrete is the most widely used construction material globally. It is crucial for buildings, roads, dams, and various infrastructure projects, providing durability and structural integrity to buildings. However, the production of concrete involves the use of cement, which is a primary source of CO_2 emissions. The chemical process of making cement, known as clinker production, is carbon intensive.

The cement industry is responsible for a substantial share of global CO_2 emissions, primarily due to the chemical process of calcination, where limestone is heated to produce clinker, the primary ingredient in cement (Figure 30). Moreover, the energy-intensive nature of cement production further exacerbates its carbon footprint.

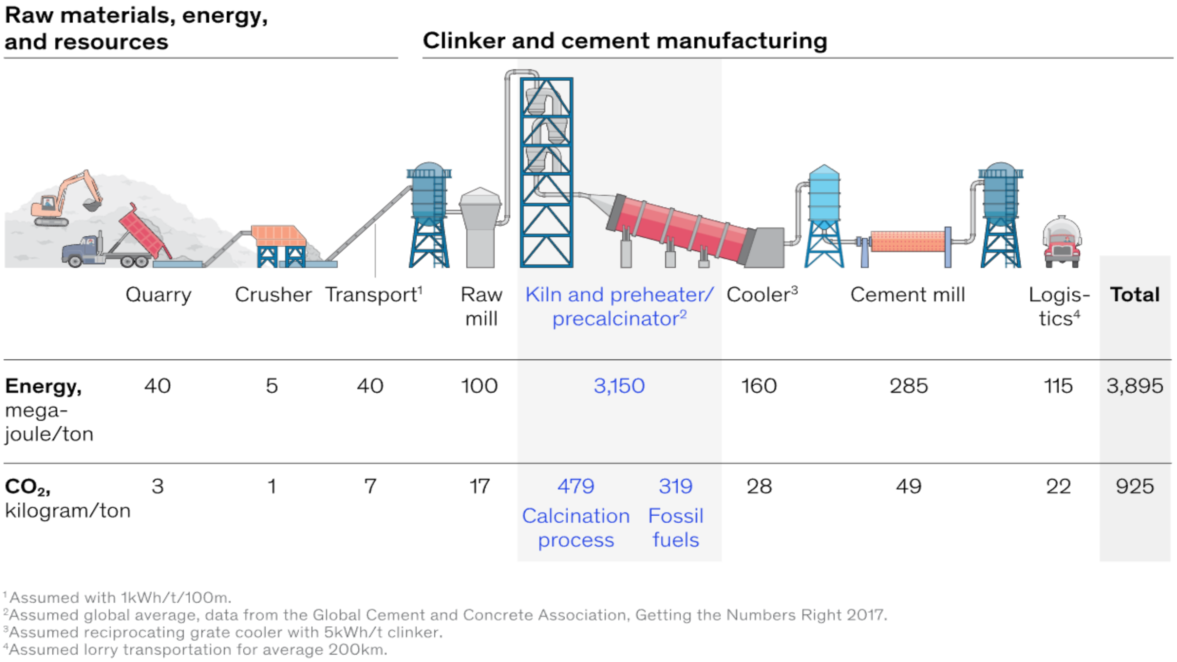
Figure 30. Cement Manufacturing Process



Source: Waldrop, M. (2022). The road to low-carbon concrete. Knowable Magazine.

Traditional decarbonization solutions, like electrification, may reduce emissions from energy use, but they cannot fully address around 50% of the emissions associated with cement manufacturing (Figure 31).[105] Emissions mitigation strategies for the cement and concrete industries include the use of alternative, lower-carbon binders, and supplementary cementitious materials, improving energy efficiency, reducing the amount of clinker in cement, and exploring carbon capture utilization and storage technologies.[106]

Figure 31. Cement production and calcination reaction, the sources of CO_2 emissions



	Raw materials, energy, and resources			Clinker and cement manufacturing						
	Quarry	Crusher	Transport[1]	Raw mill	Kiln and preheater/ precalcinator[2]		Cooler[3]	Cement mill	Logistics[4]	**Total**
Energy, mega-joule/ton	40	5	40	100	3,150		160	285	115	3,895
CO_2, kilogram/ton	3	1	7	17	479 Calcination process	319 Fossil fuels	28	49	22	925

[1] Assumed with 1kWh/t/100m.
[2] Assumed global average, data from the Global Cement and Concrete Association, Getting the Numbers Right 2017.
[3] Assumed reciprocating grate cooler with 5kWh/t clinker.
[4] Assumed lorry transportation for average 200km.

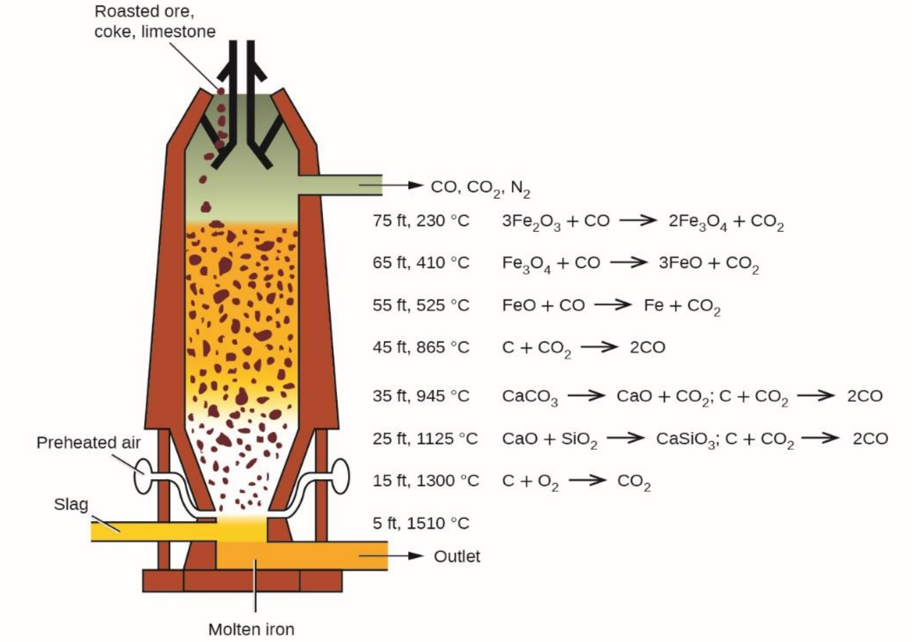
Source: Czigler, T., Reiter, S., Schulze, P., & Somers, K. (2020). Laying the foundation for zero-carbon cement. McKinsey & Company

Like concrete, the steel industry is essential for constructing buildings and bridges. It is also essential for vehicles and machinery, and critical to making renewable technologies such as wind turbines. It is a cornerstone of industrial development, transportation, and infrastructure projects.

Steel can be manufactured using two main methods: an integrated or an all-electric approach. Steel production primarily relies on the reduction of iron ore with carbon in a blast furnace, a process that releases substantial CO_2 emissions. Electrification in the steel industry can mitigate emissions to some extent, particularly by using electric arc furnaces (EAF), but the global manufacturing process still poses challenges for decarbonization. In the U.S., most crude steel production – around 69% -- uses the all-electric approaches. In the EU and worldwide, the EAF approach accounts for 44% and 30% of total crude steel production, respectively, according to 2021 data.108

As noted, steel is produced from iron ore and coal or coke in a blast furnace (BF) and a basic oxygen furnace (BOF) (Figure 32).[107] This method, while highly energy-efficient, results in significant CO_2 emissions. The integrated approach is the dominant method for global crude steel production, accounting for nearly 71% of total crude steel production. In European steel production, the BF-BOF approach constitutes approximately 56% of total steel production, whereas in the USA, only 31% of steel is produced through the integrated approach.[108]

Figure 32. Blast furnace process for producing molten iron with associated temperatures and chemical processes



Source: Flowers 2023

Traditional steelmaking methods, such as the blast furnace process, are particularly carbon-intensive, making the industry a significant contributor to global CO_2 emissions. Like the cement industry, the steel sector primarily relies on the heat demands necessary for operating a blast furnace and chemical reactions that produce CO_2 as a byproduct.

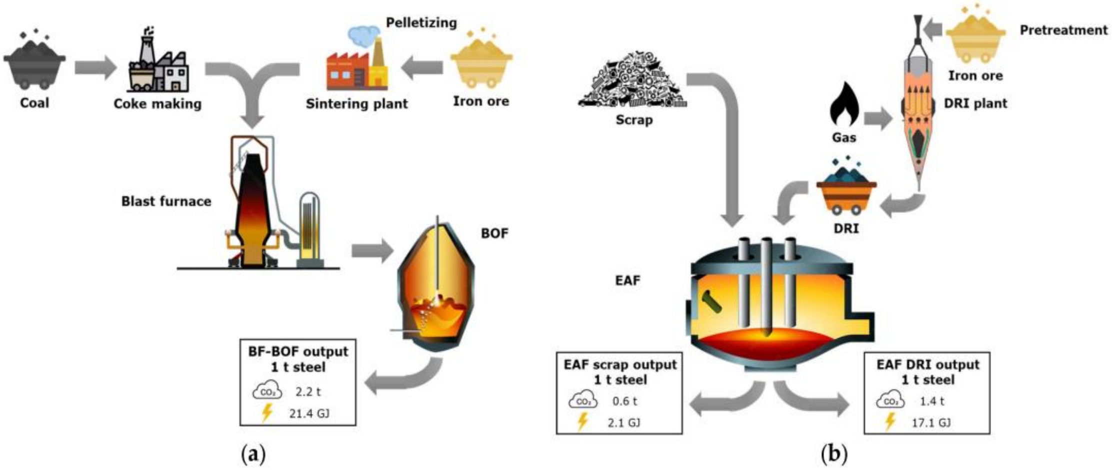
As seen in the figure, the CO_2 emissions amount to approximately 2.2 tons of CO_2 per ton of crude steel produced. In their report, Rodriguez et al. note that these emissions vary from country to country, with most countries falling within the range of 1.8 to 4.0 tons of CO_2 per ton of crude steel. Notably, China and the EU report lower CO_2 emissions, at 1.84 tons of CO_2 and 1.81 tons CO_2 respectively, while South Africa and India generate more than 3.8 tons of CO_2 per ton of steel.[109]

The “all-electric approach” involves melting scrap in an EAF; this could significantly reduce CO_2 emissions compared to the BF-BOF approach. Another method to reduce CO_2 emissions from the integrated approach is by utilizing an alternative iron source in the EAF, such as direct reduced iron (DRI) produced with natural gas (NG).[110] Fig. 33 shows the scrap-EAF and DRI-EAF processes, the emissions from which generally range from 0.6 to 1.4 tons of CO_2 per ton of crude steel, depending on the raw materials used.[111]

Efforts to mitigate CO_2 emissions in the steel manufacturing industry include the adoption of cleaner fuels like biomass or cleaner technologies like hydrogen-based processes, the use of EAF with Direct Reduced Iron (DRI) or steel scrap, the adoption of CCUS technologies, or the increase of recycling. However, decarbonizing the steel industry hinges on assessing the availability of energy and materials crucial for steel production. Decarbonization initiatives must be accompanied by considerations regarding technological maturity, supply aspects, infrastructure availability, energy and raw materials, plant-specific investment cycles, and financial and legislative conditions.

The decarbonization can be facilitated by transitioning to a hydrogen-based steel industry, adapting fossil-fuel-based steel processes for CCUS, and increasing the use of scrap and steel byproduct recycling. Energy, feedstock, and carbon storage emerge as the pivotal elements in addressing this formidable challenge.[112]

Figure 33. Energy consumption and CO2 emissions in steel manufacturing for: (a) Blast Furnace;(b) Electric Arc Furnace.



Source: Flowers 2023

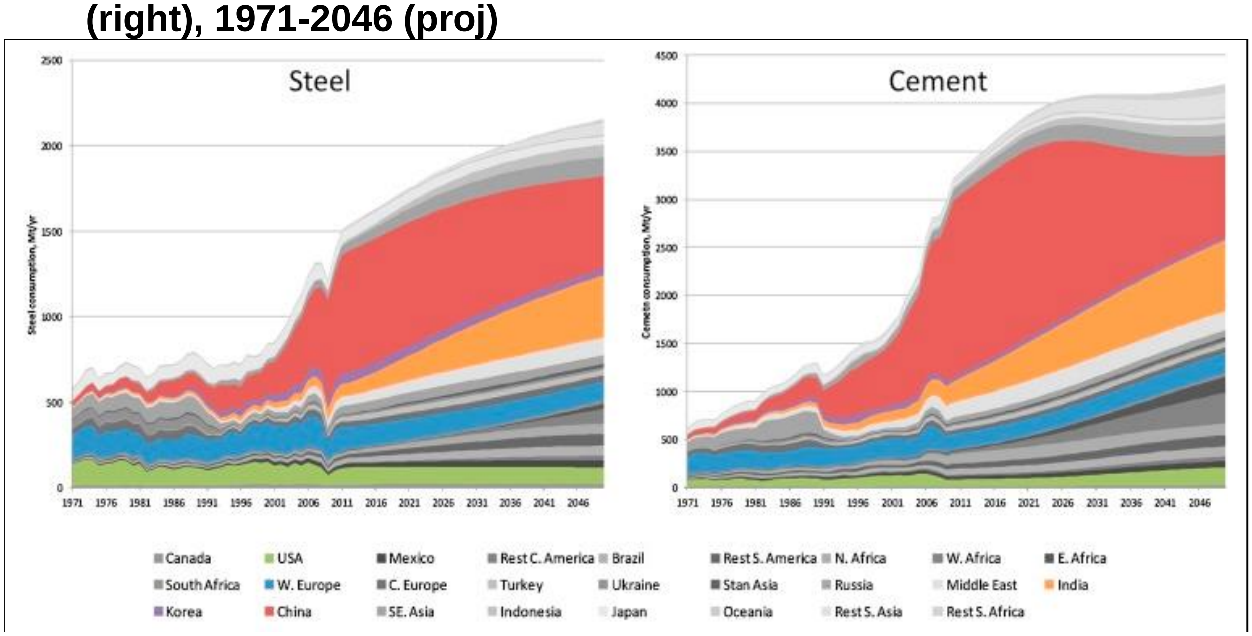
The importance of these industries is unquestionable, but their contribution to global CO_2 emissions is a critical issue. As developing countries continue to urbanize and industrialize, the demand for steel and concrete is expected to increase,[113] especially in China and India (Figure 34). Without emissions mitigation strategies, this will likely lead to higher greenhouse gas emissions. Balancing the need for steel and concrete with sustainability goals is a challenging task, necessitating a reduction in emissions while maintaining their essential role in development.

Finally, regulatory pressures and market demand are encouraging these industries to invest in cleaner technologies and reduce emissions. The steel and concrete industries are integral to global development, but their role in CO_2 emissions is a significant concern. Efforts to reduce their environmental impacts are essential for addressing climate change and ensuring a more sustainable future. These industries are actively working on adopting cleaner and more efficient practices to mitigate their carbon footprint while continuing to meet the world's infrastructure and construction needs.

6.2.1. Decarbonization Strategies for Steel and Cement

Ongoing research and technological advancements are helping reduce the carbon footprint of these industries. Innovations in production methods, the use of cleaner energy sources, and increased recycling can all contribute to emission reductions. To tackle these hard-to-abate emissions, various approaches are required:

Figure 34. National/regional consumption of steel (left) and cement (right), 1971-2046 (proj)



Source: Van Ruijven, B.J., Van Vuuren, D.P., Boskaljon W. (2016). Long-term model-based projections of energy use and CO2 emissions from the global steel and cement industries. Resource, Conservation and Recycling. 112. 15-36.

1. **Electrification:** Shifting industrial processes towards electricity-based systems is a crucial step in reducing CO_2 emissions. This includes using electric arc furnaces in steelmaking and electrifying some cement production processes where feasible.
2. **Energy Efficiency:** Improving the energy efficiency of industrial processes can significantly reduce emissions. This involves optimizing existing processes and adopting advanced technologies to minimize energy consumption.
3. **Low-Carbon Fuels:** Using low-carbon or renewable energy sources such as hydrogen or biomass can help replace fossil fuels in the industrial sector, reducing emissions from energy-intensive processes.
4. **CCUS:** These technologies are essential for capturing CO_2 emissions from industrial processes and storing or utilizing them when no other technical solutions exist.
5. **Circular Economy:** Implementing a circular economy approach, where materials are recycled and reused, can minimize the need for new production and reduce emissions associated with raw material extraction and processing. It is, however, easier to implement in the steel industry than the concrete industry.

The Cement Industry

As seen in Figure 31, the main source of CO_2 emissions in cement manufacturing is the clinker and the associated fossil fuel use at this stage of the production process. The segment encompassing the kiln, the preheater, the pre-calcinator and the cement mill account for more than 94% of the CO_2 emissions. The calcination process accounts for around 52% of the CO_2 emissions and the kiln for 34%. Electrification of the kiln has the potential to contribute to cement industry decarbonization.

VTT, a Finish research organization, has conducted successful experiments using an electric kiln for cement production. This electric kiln, powered by low-emissions electricity, offers the potential to significantly reduce carbon emissions in the cement industry. VTT's electric kiln, that was operational between November 2021 and October 2022, demonstrated that it could make cement production nearly carbon-neutral and capture pure CO_2 during the pre-calcination phase. This captured CO_2 can be used for various industrial applications or permanently trapped in concrete. VTT is seeking partnerships with major industrial players to scale up this solution. This innovative approach could revolutionize the cement industry, making it more environmentally friendly and contributing to global decarbonization efforts.[114]

CEMEX and Coolbrook, a Finnish-Dutch company, are exploring innovative technology for electrifying the cement kiln heating process. Coolbrook's patented Roto Dynamic Heater technology replaces fossil fuels with electricity to heat cement kilns at high temperatures necessary for cement production.

The Steel Industry

Globally, steel production is highly reliant on coal, which currently meets around 75% of the energy and feedstock demand of the sector, roughly the same share over the past decade.[115] Coal is primarily used as a reducing agent to extract iron from iron ore and to provide the carbon content needed in steel.

Importantly, the steel industry has made substantial progress in decarbonization through the development of electric arc furnace technologies (EAFs). EAFs use electricity to melt scrap steel, eliminating the need for traditional blast furnaces that rely on coal or coke. Electrification through EAFs can significantly reduce carbon emissions in steel production. However, EAFs and blast furnaces are two distinct methods for producing steel in the steel industry, and they serve different purposes. Whether EAFs can replace Blast Furnaces depends on various factors, including the type of steel production, the desired end products, environmental considerations, and economic factors (Table 1).

In summary, EAFs are well-suited for recycling scrap steel and producing certain types of steel products, especially in regions where environmental regulations are strict or clean energy sources are abundant. However, Blast Furnaces are still necessary to produce primary steel from iron ore, and in some cases, a combination of both methods may be employed to meet different steel production needs while addressing sustainability goals.

Table 1
Comparison of Blast Furnace and Electric Arc Furnace

	Raw Materials	Environmental Impact	Product Quality	Economic Factors	Operation
Blast Furnace	Iron ore, coke, limestone	Higher carbon footprint	High-quality steel	Requires significant capital investment	Hard to replace or shut down
EAF	Scrap steel	Lower carbon footprint	Scrap steel quality	More cost-effective	More flexible

To enhance the efficiency and sustainability of steel production, EAF can be combined with the utilization of DRI. DRI is a form of iron that is produced by reducing iron ore in a process that emits significantly less carbon dioxide compared to the conventional integrated steelmaking process. Direct reduction methods can be categorized into two groups: those that rely on gas and those that rely on coal. In both instances, the primary goal is to eliminate the oxygen present in the iron ore. This is done to transform the ore into metallic iron without the need for melting, and the process operates at temperatures below 1,200 °C (2,190 °F). This approach facilitates the production of high-quality steel products within the EAF.[116]

The quality of steel products is closely linked to the availability of high-grade steel scrap. In situations where such scrap is scarce, the integration of DRI into the production process becomes essential to guarantee specific product qualities. It's worth noting that the production of DRI relies on the availability of economical and easily obtainable natural gas or coal. As a result, regions with lower natural gas prices, such as the Middle East or North America, have become major producers of DRI, while its utilization is less common in Europe. In some European steelmaking operations, a derivative of DRI known as Hot Briquetted Iron (HBI), which is a more transportable form of DRI, is imported. HBI is incorporated into the steelmaking process either in the traditional Blast Furnace method to optimize the mix of materials, or in the EAF where it is blended with scrap to enhance the quality of the steel product. This approach aligns with the objective of improving the efficiency and environmental sustainability of steel production.

6.2.2. Low-Carbon Fuels

Low-carbon fuels, such as hydrogen or biomass, have the potential to play a significant role in replacing fossil fuels in the cement and steel industries.

Hydrogen

Hydrogen is emerging as a versatile and clean energy carrier. In the cement industry, hydrogen can be used as a reducing agent, replacing traditional fossil fuels in the clinker production process, thereby reducing CO_2 emissions. Similarly, in the steel industry, hydrogen can be utilized as a reducing agent in the direct reduction of iron ore, leading to lower carbon emissions compared to the conventional blast furnace method. The adoption of hydrogen, particularly green hydrogen produced using renewable energy, can significantly contribute to decarbonizing both industries.

Hydrogen serves as a game-changer in the steel industry by offering a clean alternative to the carbon-intensive processes associated with blast furnaces. Green hydrogen, produced through renewable energy-powered electrolysis, can act as a reducing agent in steelmaking, significantly reducing carbon emissions. This transition not only lowers the carbon footprint but also enhances overall sustainability. Here are some examples of how hydrogen and natural gas are revolutionizing the steel industry.

- In China, Sinosteel Engineering & Technology contracted for a hydrogen-based “ENERGIRON” direct reduction (DR) plant with a capacity of 1,000,000 tons per year. This plant will become China's largest hydrogen-based DRI facility and part of the global effort to reduce carbon emissions in the steel industry by replacing traditional blast furnace methods with more sustainable alternatives, particularly gas-based ironmaking technologies. The new plant will primarily use hydrogen as the reducing gas, with the option to mix it with a Natural Gas and Coke Oven Gas (COG). The facility can also capture and sell CO_2, further reducing emissions and generating additional revenue. The plant will produce cold DRI pellets with potential future hot DRI production and transport to an adjacent EAF mill.[117]

- Baowu Group, the world's largest steelmaker, developed a roadmap to reduce carbon emissions per metric ton of crude steel by 30% from 2020 to 2035 and achieve carbon neutrality by 2050. Decarbonization of the steel industry, accounting for 15%-20% of China's annual carbon emissions, is vital to achieving these goals. To attain carbon neutrality, some steelmakers are focused on blast furnace and converter technologies, while smaller mills may transition to EAFs. Some analysts predict that in the future 50% of China's crude steel capacity will be EAFs. Baowu is also testing hydrogen-rich blast furnace technology and pure hydrogen furnace technology with plans to build hydrogen-based facilities and EAFs to promote a sustainable steel industry.[118]

- German industrial and technology group Thyssenkrupp is collaborating with energy firm STEAG on the “HydrOxy Hub Walsum project,” a 500MW hydrogen electrolysis power plant for metals production. The project to produce renewable hydrogen will be connected to the grid by 2025. Close to Thyssenkrupp's Duisburg steel mill, proximity to the mill reduces the need for an elaborate supply system. The project is a crucial step in decarbonizing German steel production and is a test case for potential expansion across Europe. It also aligns with the hydrogen goals of both the German government and the European Union.[119]

In the cement industry, hydrogen holds the potential to transform clinker production. By utilizing hydrogen as a high-temperature energy source, cement plants can reduce their emissions and minimize their environmental impact. Green hydrogen or hydrogen, coupled with carbon capture and utilization, offers a solution for a more sustainable cement production process. However, considerable progress would be required to bring it to commercialization and enable it to compete with alternatives. Furthermore, the technology would address energy but not process emissions from cement production.

Biomass

Biomass, sourced from organic materials like wood and agricultural residues, represents a renewable and carbon-neutral fuel option. When used in the cement and steel industries, biomass can theoretically replace fossil fuels, thereby reducing carbon emissions. Co-firing biomass in cement kilns and using it as an energy source in steelmaking processes leads to reduction in the carbon footprint.

Additionally, carbon capture and utilization (CCU) can be integrated with biomass combustion to achieve carbon-negative emissions. In the steel industry, biomass can be utilized as a source of carbon in the production of DRI in EAFs, helping to reduce the carbon footprint of steelmaking. Biomass injection into blast furnaces is currently in commercial use in Brazil, where it serves as a reductant. It's worth noting that not all types of biomass are suitable for direct injection into blast furnaces. Some types of biomass necessitate smaller-scale, less efficient blast furnaces due to the lower compressive strength of charcoal compared to coke.

6.2.3. Carbon Capture, Utilization, and Storage:

CCUS technologies can play a pivotal role in capturing and managing CO_2 emissions in the steel and cement industries.

CCUS involves capturing CO_2 emissions at the source, preventing them from being released into the atmosphere. In the cement industry, CO_2 capture technologies can be applied to the cement kilns, where the chemical conversion of limestone into clinker generates significant CO_2 emissions. In the steel industry, carbon capture can be integrated into the steelmaking process, especially in facilities using blast furnaces and other high-emission operations.

Captured CO_2 can be used in various ways. In the cement sector, CO_2 can be used to produce construction materials like aggregates, or in the formation of low-carbon cements, which can reduce emissions further. In the steel industry, CO_2 can be used in the production of synthetic fuels and chemicals. In addition, electrification can facilitate the deployment of carbon capture and utilization (CCU) technologies. The electricity required to operate these CCU processes can be sourced from renewable energy, making the capture and storage of carbon emissions more sustainable.

CO_2 that is captured but not immediately utilized can be safely stored underground in geological formations, preventing its release into the atmosphere. Below are examples for CCUS in the cement industry:

- HeidelbergCement and its Swedish subsidiary Cementa have unveiled positive results from a pre-feasibility study for the Slite CCS project, a significant step towards the industry sustainability targets. The project is located at the Slite cement plant in

Sweden and aims to capture up to 1.8 million tons of CO_2 annually, equivalent to three percent of the country's total emissions. It is the largest CCUS project for the cement industry. The technology used for carbon capture is amine capture, and the full-scale implementation will require plant modifications and increased power demand. The project leverages the plant's favorable location near a sea-harbor and aims to produce carbon-free cement for the Swedish construction industry. It builds on the experience gained from the Brevik CCS project in Norway, set to be operational in 2024.[120]

- Air Liquide, a French company, has secured EU funding to develop two CCS projects at cement factories in Poland and France. The first project, called Go4ECOPLANET, aims to completely decarbonize cement production at a Lafarge plant in Kujawy, Poland. It involves a unique technology to capture and liquefy CO_2 emissions, capturing 100% of the plant's CO_2 emissions and storing them in the North Sea. This project is a crucial part of Holcim Group's efforts to achieve its Net Zero Pledge and is funded entirely by the EU Emissions Trading System's Innovation Fund, resulting in 105% greenhouse gas emissions avoidance compared to a reference scenario. It is expected to start operation between late 2027 and early 2028.[121]

The second project, known as the K6 Program, will transform a historic cement plant in Hauts-de-France, France, into the first carbon-neutral cement plant in Europe. The plant has a significant capacity and utilizes local waste materials, providing jobs and serving a regional market. The K6 Program will employ an innovative combination of an airtight kiln and cryogenic carbon capture technology to capture and store CO_2 emissions in the North Sea. Over the first ten years of operation, it is expected to avoid 8.1 million tons of CO_2eq emissions. Additionally, the project will support the development of the nearby Port of Dunkirk as a European CO_2 hub. Both projects aim to contribute to decarbonizing the construction industry and are set to commence operations in the late 2020s.[122]

6.2.4. Examples of Steel Industry CCS Projects

Direct reduced iron plants, where iron ore is turned into iron without melting (usually using natural gas or coal), could be upgraded with a CO_2 capture system that relies on a chemical reaction between CO_2 and a solvent (like amine-based). This process captures CO_2 and then releases it at temperatures between 120°C to 150°C, allowing the solvent to be reused.

- Since 2008, two operating plants of Tenova in Mexico have been capturing 5% of emissions (approximately 0.15-0.20 million tons per year combined). Tenova DRI plants, which use natural gas, can already reduce CO_2 emissions by over 50% compared to traditional blast furnace methods. Moreover, Tenova has implemented CO_2 absorption units that capture around 250 kilograms of CO_2 for every ton of steel produced using DRI technology, out of the total 400 kilograms of CO_2 generated in the process. This unique feature is also present in both the Guerrero and Puebla Ternium DRI modules, and the captured CO_2 is sold to the beverage industry as an end-user, contributing to the reduction of emissions.[123]

- Emirates Steel, in partnership with Al Reyadah, pioneered a CCUS project in Abu Dhabi, which started in November 2016. The project is a joint venture between Abu Dhabi National Oil Company (ADNOC), Masdar and Emirates Steel Industries. It captures CO_2 from their steel production facility and uses it to enhance oil and gas recovery. It aimed to reduce carbon emissions and contribute to Abu Dhabi's sustainability goals. The project successfully captured a significant amount of CO_2, equivalent to removing emissions from 170,000 cars. This approach showcased the effectiveness of CCS in steel production and increased oil recovery by 10%. Emirates Steel is committed to sustainability and holds several certifications and standards related to environmental responsibility. They are also working on a green hydrogen project in collaboration with TAQA to achieve green steel production and further reduce energy consumption and carbon emissions.[124]

6.2.5. Technology Innovation

The following section is a tertiary examination of technical innovations in both the cement and steel industries sub sectors.

Cement Industry

CO_2 from industrial sources can be utilized to produce building materials, notably through CO_2 curing in concrete production and by reacting CO_2 with waste materials (e.g., iron slag, coal fly ash) to create construction aggregates. CO_2 curing in concrete production is a process that involves using CO_2 as a curing agent to enhance the properties of concrete. These approaches offer CO_2 storage within the building materials, potentially reducing costs and avoiding conventional waste disposal expenses. However, energy-intensive processes, especially in pre-treatment and post-treatment steps, are associated with producing building materials from waste.[125]

CO_2 sequestration in carbonates offers semi-permanent CO_2 storage options and potential cost reductions in concrete production. It requires effective carbon capture technologies to achieve emission reductions, but if CO_2 is sourced from non-cement industrial sources, it doesn't directly reduce CO_2 emissions from cement production. Examples of CO_2 sequestration in inert carbonate materials initiatives include:

- Carbon8 in the UK uses high-purity CO_2 to convert air pollution control residues into carbon-negative aggregates for building materials. They have conducted successful demonstration projects in Canada, the United States, and France and are piloting a waste and CO_2 aggregate production system in the Netherlands.
- The CO2Min project, led by Heidelberg Cement and RWTH Aachen University, explores CO_2 absorption from flue gas by minerals like olivine and basalt.
- The FastCarb project in France investigates accelerated carbonation in recycled concrete aggregates.

- CarbonCure, a Canadian company, offers a commercial CO_2 curing process available in numerous concrete plants, claiming improved compressive strength and cost-effectiveness.
- CO2-SUICOM, developed by Kajima Corporation and others, uses a powder to reduce CO_2 emissions in concrete and is commercially available in Japan, with practical applications in construction.

Steel Industry

In traditional blast furnace steelmaking, carbon monoxide is primarily used as a reducing agent, and it is typically generated on-site through the partial oxidation of coke. An approach to emissions reductions: capturing and reusing the carbon dioxide byproduct resulting from this process through a thermochemical CO_2 splitting process. This would create a self-contained carbon cycle, eliminating the need for additional coke consumption in the production process.

Researchers at the University of Birmingham and the University of Science & Technology Beijing conducted a study that identifies a cost-effective decarbonization approach through the coupling a thermochemical CO_2 splitting cycle with existing blast furnace-basic oxygen furnace (BF-BOF) steelmaking processes. The key element in this approach is a perovskite material which can efficiently split CO_2 into carbon monoxide (CO) at low temperatures and with high selectivity. The CO generated in this cycle can replace expensive metallurgical coke in the blast furnace for iron ore reduction. Additionally, the CO_2 produced by the blast furnace can be fed back into the thermochemical cycle to generate more CO, creating a closed carbon loop.[126]

6.2.6. Circular Economy and Recycling

Cement Industry

Several methods have been developed to recycle concrete, with one approach focusing on producing crushed concrete fines, which are fine particles ranging from 0 to 4 mm in size. This method allows for the recovery of calcium oxide (CaO) from these fines, which can then be employed in cement kilns to substitute a portion of the limestone (CaCO3) typically used as an input. This substitution significantly reduces process emissions, estimated to be around three times less.125 Additionally, the recovered CaO can serve as a filler in blended cements. Furthermore, when concrete is crushed into its individual components, it yields old cement powder. This powder can initially replace lime flux in steelmaking and subsequently be used as zero-emission clinker in cement production. In the steelmaking process, lime flux is a chemical substance (typically CaO) that is added to the furnace or vessel where steel is being produced.

Another method to recycle cement is: Unhydrated cement recycling. During the concrete curing process, a portion of the cement may not interact with water and remains unhydrated. Some estimates indicate that as much as 50% of the cement might stay unhydrated.

Researchers are working on innovative concrete crushing methods that could potentially retrieve this unhydrated cement from old concrete, allowing it to be reused directly as new cement.

Steel Industry

A team of engineers from Cambridge has developed a groundbreaking invention – the world's first emissions-free method to recycle Portland cement. This innovative process combines steel and cement recycling, powered by renewable electricity, and it has significant implications for creating the basic materials for construction in a zero emissions world. This new approach recycles concrete waste from demolished buildings and reuses old cement powder in a way that eliminates emissions associated with cement production.

The process starts by taking old concrete from demolished buildings. It is then crushed to separate the rocks and sand from the mixture of cement powder and water that holds them together. Then, instead of using a substance called lime-flux in the process of recycling steel, the old cement powder is used. When the steel is melted, this cement-like substance creates a layer on top of the liquid steel to protect it from the air. After the recycled steel is removed, it is quickly cooled then this cement-like layer is crushed into a powder. In tests, the Cambridge team has shown that this recycling process produces a material with the same chemical composition as that of regular cement.

The development of this emissions-free cement is part of the UK FIRES program, aimed at achieving a rapid transition to zero emissions using existing technologies. The project has received a £1.7 million ($2.08 M) research grant from the Engineering and Physical Sciences Research Council (EPSRC) to further study and optimize the process. If successful, this innovation has the potential to revolutionize the construction industry, securing a sustainable supply of materials while supporting economic development.[127]

6.2.7. Challenges to implementation of decarbonization strategies

Implementing decarbonization strategies in the steel and cement industry presents a number of challenges. Technological innovation plays a pivotal role in the transition to more sustainable production processes, yet developing and deploying these technologies at the scale required for these industries is a challenge. Breakthrough innovations, such as electrification processes, direct reduction methods, hydrogen-based steelmaking, advanced carbon capture and utilization technologies, and recycling need substantial research, development, and capital investment.

The electrification of steel production results in a significant reduction in CO_2 emissions, facilitated by the EAF's advantages of using scrap steel and adapting to cleaner energy sources. However, certain factors maintain the widespread use of the BF-BOF route. The historical infrastructure of existing BF facilities requires substantial capital and time for a successful transition from BF/BOF to EAF. Regions with abundant, reasonably priced coal and iron ore continue to find the BOF method attractive. Meeting specific steel chemical composition requirements, particularly in Europe, poses challenges using EAF. Although mini mills have shifted toward more environmentally conscious practices, they encounter difficulties in matching the integrated techniques for top-quality steel production.[128]

Given the complexity of maintaining precise control over scrap to produce high-quality steel, the EAF with DRI and scrap route meets all the criteria: high-grade steel production, minimal CO_2 emissions, and significant potential for implementing CO_2-free processes.

Regarding CCUS technology deployment, there are challenges to widespread CCUS adoption in these industries, including high costs, technical feasibility, public acceptance, and regulatory frameworks. Additionally, the availability of suitable geological storage sites and infrastructure is a key consideration for the successful deployment of CCUS. Despite these challenges, CCUS remains a critical tool in the toolkit for reducing emissions in these heavy industries and advancing global efforts to combat climate change.

Moreover, for the other strategies mentioned, the capital costs associated with these innovative technologies present a significant barrier. Retrofitting existing facilities or building new ones that incorporate decarbonization solutions is costly. These costs can be a substantial deterrent, especially when the return on investment is uncertain. Infrastructure and supply chain concerns also come into play. For example, a widespread transition to green hydrogen requires the development of an entirely new supply chain. Ensuring a reliable and sustainable supply of green hydrogen, which promotes low-carbon steel and cement production, is a challenge that demands significant infrastructure investments.

In addition, the partial substitution of hydrogen in blast furnaces, even for existing operations, can contribute to emissions reduction. However, it's important to note that currently hydrogen alone cannot entirely replace the coal requirements in blast furnaces for steel manufacturing. Therefore, this approach only leads to a partial reduction in emissions.

Competitiveness on the global market is also a significant issue. The steel and cement industries are global, and price competitiveness is paramount. Adopting expensive low-carbon technologies can put regions and companies at a disadvantage in the global market if competitors can produce more affordably using conventional methods. In addition, regulatory and policy frameworks play a crucial role in encouraging or discouraging decarbonization efforts. Fluctuating regulations can deter investment in low-carbon technologies, and inconsistent policies across regions can create uncertainty for industry players.

Carbon pricing is both a solution and a challenge. While carbon pricing mechanisms can incentivize emissions reductions, they can also impact the competitiveness of energy-intensive industries. Striking a balance between environmental goals and industrial competitiveness is a delicate challenge.

Finally, resource availability is another obstacle in implementing sustainable practices in these industries. Sourcing essential raw materials like iron ore and limestone for steel and cement production can be limited in certain regions, making it challenging to implement circular economy and recycling practices that rely on these raw materials. Consequently, the steel and cement industries face the challenge of balancing emissions reduction with competitiveness and long-term sustainability as they strive to achieve ambitious environmental objectives.

China, the world's largest steel producer, plans to include heavy industry emissions in its Emissions Trading System (ETS) by 2023 or 2024. As part of its 14th Five-Year Plan (2021-2025), China aims to promote a circular economy, targeting a rise in scrap steel usage to 320 million tons by 2025 and aiming to reach peak steel production and reduce sectoral emissions before 2030. India, the second-largest steel producer globally, is also prioritizing scrap steel to cut the carbon intensity of domestic steel production in half by 2030. Numerous countries unveiled strategies to decarbonize their cement sectors. China collaborated with the Rocky Mountain Institute to formulate its roadmap, although the inclusion of cement in China's ETS was delayed.

In the United States, federal initiatives, such as the IRA and the Bipartisan Infrastructure Law (BIL), include provisions to support the development of low-carbon technologies and the modernization of critical infrastructure. These policies aim to stimulate innovation and incentivize the transition to more sustainable steel and concrete production methods.

Ultimately, overcoming the barriers to decarbonizing the steel and concrete industries requires a coordinated effort from governments, industry stakeholders, and international partners. The development and adoption of low-carbon technologies and sustainable practices are essential not only for reducing emissions but also for ensuring the long-term viability and competitiveness of these critical sectors in a carbon-constrained world.

6.2.8. Case Study Summary

The steel and concrete industries play vital roles in shaping global infrastructure and fostering development, including the key building blocks for renewable implementation. Yet, they stand out as energy-intensive sectors with notable environmental consequences. Together, they contribute to approximately 15% of the world's CO_2 emissions. The challenges in these sectors are further exacerbated by their energy-intensive manufacturing processes, coupled with the inherent chemical reactions that release CO_2 as a significant byproduct. This combination of factors underscores their status as "hard-to-abate" sectors, posing substantial challenges to achieving substantial emissions reductions.

While electrification has emerged as a crucial element in reducing emissions, this paper underscores that it is merely one piece of the puzzle. Industrial decarbonization does not have a one-size-fits-all solution; instead, it requires a multitude of approaches and strategies. Showcasing the different nature of decarbonization strategies is paramount in addressing the scope and complexity of the problem.

This case study examined a range of strategies, including electrification, the adoption of low-carbon fuels, improvements in energy efficiency and new technologies, the integration of circular economy and recycling practices, and the deployment of CCUS technologies. The potential for substantial reductions in carbon emissions is examined and showcased. The presented case studies exemplify real-world initiatives and the feasibility of these strategies in the steel and concrete industries. They demonstrate that success is achievable with the right combination of technology, innovation, and commitment to sustainability.

The barriers and challenges that lie ahead are acknowledged, including cost considerations, technological readiness, and the necessity for policy support. The need for collaborative efforts among governments, industries, and researchers is emphasized. Policymakers should consider supportive regulations and incentives, and industries must embrace innovative solutions, investing in research and development.

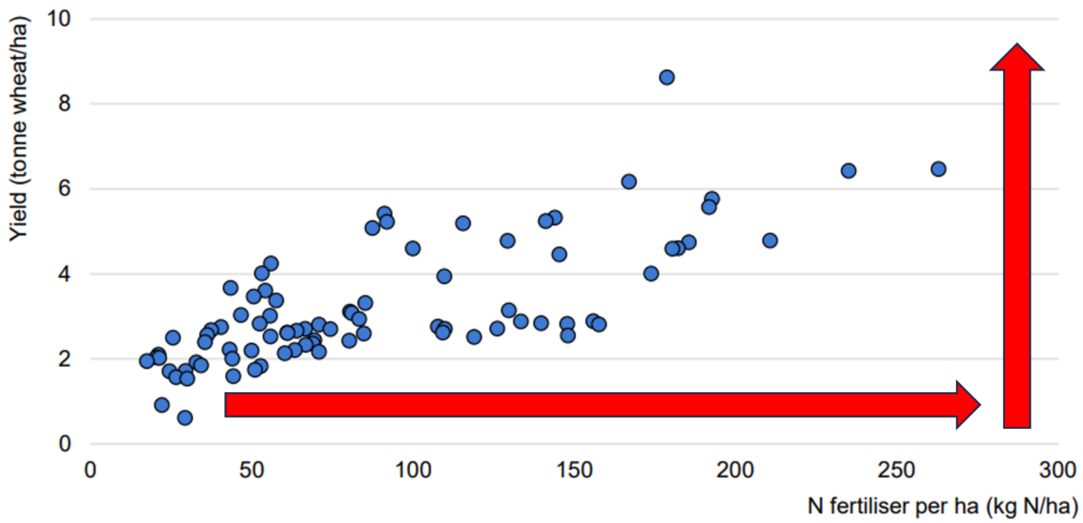
Finally, while the challenges of decarbonizing these industries are considerable, the benefits are equally substantial. The industrial carbon footprint can be significantly reduced by embracing electrification, low-carbon fuels, increasing energy efficiency, practicing circular economy principles, and integrating CCUS technologies. The time has come to shift beyond a one-size-fits-all solutions and rather embark on a comprehensive journey toward a more sustainable, low-carbon future for the industry.

6.3. Global Food Security: Ammonia, Natural Gas and Decarbonization Needs

Ammonia is a critical ingredient for making fertilizer and natural gas is a critical feedstock for making ammonia. According to the IEA, “Ammonia is the starting point for all mineral nitrogen fertilizers, forming a bridge between the nitrogen in the air and the food we eat. About 70% of ammonia is used for fertilizers, while the remainder is used for various industrial applications, such as plastics, explosives, and synthetic fibers. The primary purpose of fertilizers is to achieve and maintain high crop yields and replenish soils with the nutrients that are depleted when plants grow. Since the early 20th century, mineral fertilizers have formed an integral part of our food system. Researchers estimate that around half of the global population is sustained by mineral fertilizers.” [129] As seen in Figure 35, wheat crop yields increase with fertilizer use (arrows added or emphasis), an indicator of the significant value of ammonia for food security.

Currently, fossil fuels are used as a feedstock for making fertilizer. According to the Energy Information Administration, globally, in 2020, 72% of the fossil fuel feedstock used for making fertilizer is natural gas and 28% is coal. In the U.S., natural gas use in ammonia production is 92% of the total. In short, ammonia is critical for food security and natural gas is critical for ammonia production. At the same time, the demand for ammonia is growing. The IEA, in its Stated Policies Scenario (2020) forecasts production increases of ammonia by almost 40% by 2050.

Figure 35. Fertilizer Use and Crop Yield for Wheat Production

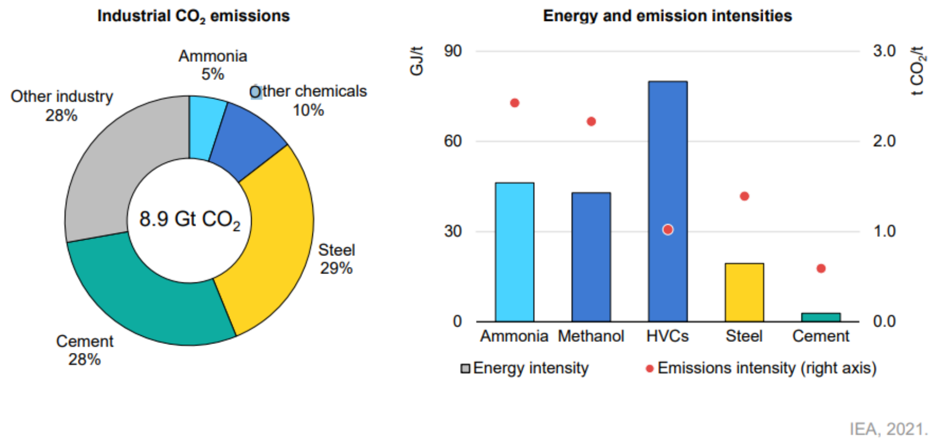


Source: IEA, 2021, Ammonia Technology Roadmap

Note: Each data point represents the average fertilizer use and yields in a specific country for the years 2006, 2007, 2010, and 2014.

Ammonia production, however, emits carbon and is also a major air pollutant. IEA notes that in 2020, emissions from ammonia production were 450 Mt of CO_2 a footprint equivalent to the total energy system emissions of South Africa." As seen in Figure 36, while ammonia is only five percent of industrial CO2 emissions, its energy intensity is greater than steel and cement and its emissions intensity is significantly higher than high voltage cables, steel, and cement. At the same time, ammonia once produced, emits no carbon. It could be used as a zero-carbon energy carrier, giving it potential value in the transportation and electricity sectors.

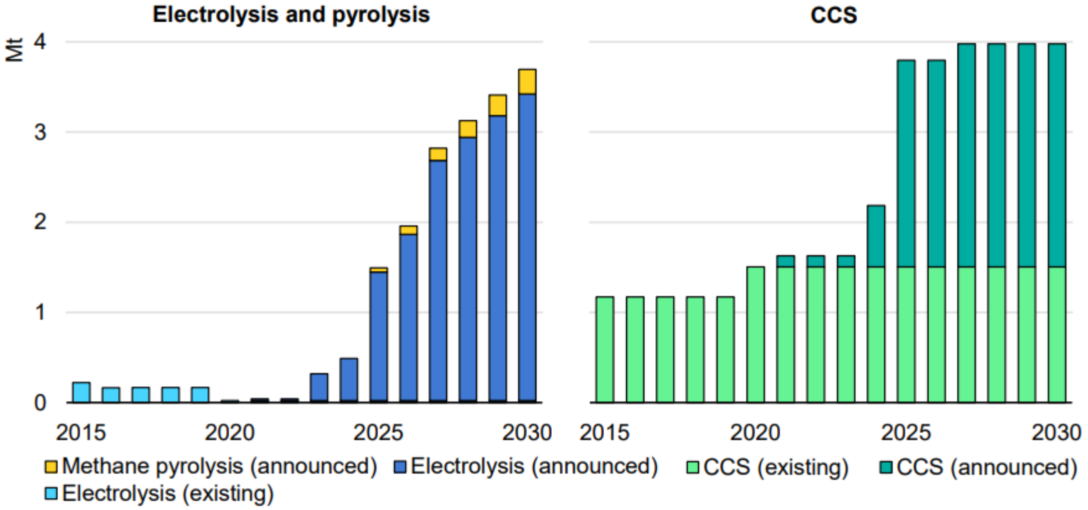
Figure 36. Energy Consumption for and Emissions from Ammonia Production, 2020



Source: IEA, 2021, Ammonia Technology Roadmap

This makes reducing emissions from ammonia a critical need for reaching net zero targets by mid-century, while ensuring the food security it provides to the world's population. Options for decarbonization include electrolysis, methane pyrolysis, and carbon capture and sequestration. Figure 37 shows current and announced projects as of 2020 focused on decarbonizing ammonia production and the volumes of CO2 these projects are designed to capture. As seen in the figure, the largest volumes of CO2 already being captured from ammonia production are from CCS plants and more significantly more volumes are planned to be captured by announced projects between 2023 and 2030. All pyrolysis and electrolysis capture projects were announced but not yet operational as of 2020, when this figure was released by the IEA.

Figure 37. Current & Announced Projects for Newrt-zero Emissions Ammonia Production

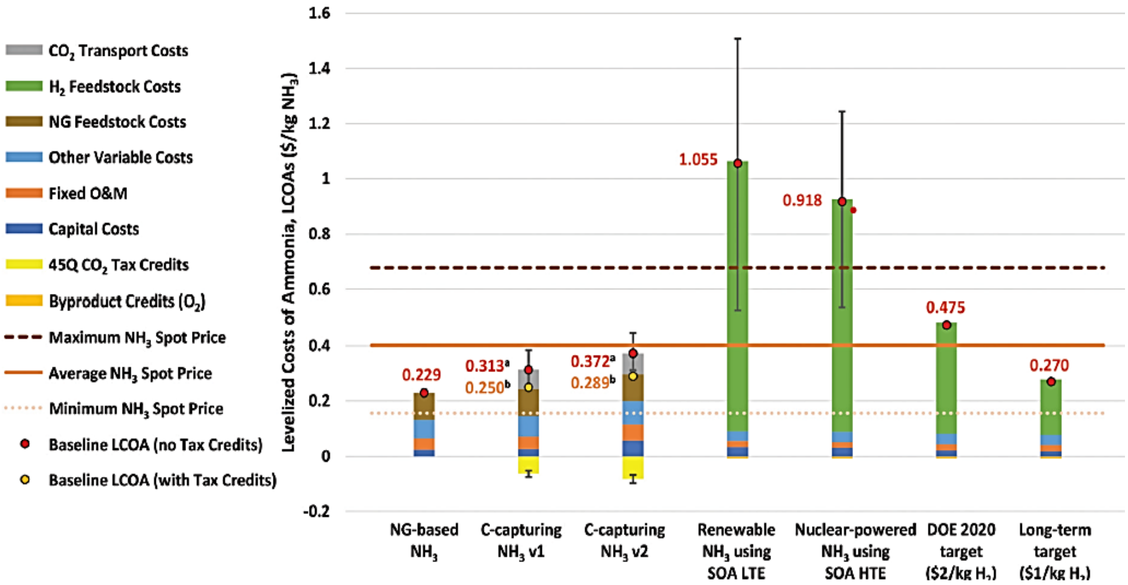


Source: IEA, 2021, Ammonia Technology Roadmap

This analysis, based om part on engineering modeling using Aspen Plus, identifies levelized costs of the range of options for ammonia production from natural gas, natural gas with carbon capture, nuclear generation, and renewables generation. As seen in Figure 38, the levelized costs of ammonia produced with renewable and nuclear generation are significantly higher than ammonia produced from natural gas with CCS.

These data, the critical role of ammonia in feeding the world's populations, and the need to lower costs of ammonia made with renewable or nuclear generation suggest a range of policy and technology pathways are essential for addressing these issues in the longer term. In the near- to mid-term, based on the analysis used to inform Figure 37, natural gas with CCS appears to be the most affordable option – and affordability is key to feeding the worlds' population. This option, however, needs policy support as well, in part to support the infrastructure and regulatory structures needed for CCS.

Figure 38. Levelized Costs of Ammonia for NG-based, Carbon-Capturing, Nuclear-Powered Renewables Ammonia Production



Source: Techno-economic performances and life cycle greenhouse gas emissions of various ammonia production pathways including conventional, carbon capture, nuclear, and renewable, Green Chem., 2022

More analysis needs to be done to review the status, costs, locations, and any policy support for the announced as well as the existing projects. Such analysis is important to understand what policies and subsidies might need to be developed/implemented to decarbonize ammonia production going forward. This is important from both a cost and process perspective. This need is underscored by a detailed analysis released by the Royal Society of Chemistry in May 2022.

7. Conclusion

The role of natural gas in industrial decarbonization is complex and presents both challenges and opportunities. As industries seek to reduce emissions and transition toward more sustainable practices, natural gas emerges as a transitional energy source to facilitate this shift. Its lower carbon intensity, existing infrastructure, and versatility make it a valuable option for achieving near-term emission reductions while serving as a foundation for long-term mitigation strategies. Natural gas has great flexibility as a switching fuel. Natural gas appears to be particularly resilient due to its ready availability, affordability, flexibility and as a necessity in hard-to-abate sectors and industries, even in countries (primarily OECD) that will reduce coal and petroleum liquids use by 2050. All these factors make natural gas a reliable source of energy to meet energy transition challenges and global decarbonization goals.

Energy transitions have been mainly led by reduced costs and increased availability of new energy resources. However, the current energy transition in some regions is now led by climate change and environmental concerns. This new parameter creates more complex energy systems where each sector must consider their environmental impacts. Carbon dioxide emissions associated with energy and industrial production can come from a range of fuel types.

Since 2010, GHG emissions from the industrial sector have increased by more than 30%. Industrial emissions have been growing faster since 2000 than emissions from any other sector, driven by increased extraction and production.[130] GHG emissions attributed to the industrial sector originate from fuel combustion, process emissions, product use and waste.

While the transition to a low-carbon economy is crucial for addressing climate change, there are concerns about how associated policies might affect key industries and their competitiveness in regional and global markets. Policies such as the CBAM could weaken European industrial competitiveness and increase economic risks. Industries that are energy-intensive may face higher energy costs due to the shift toward renewable energy sources and the implementation of carbon pricing. This could make their products less competitive in global markets, potentially leading to a loss of market share and eventually loss of jobs, and essentially export carbon intensive production to other countries. This can undermine the intended emissions reduction and harm the economy of the countries issuing carbon regulations. In addition, the costs associated with decarbonization efforts, such as subsidies and energy-efficient upgrades, would be passed on to consumers in the form of higher prices on goods or in higher taxes.

Even though recent global CO_2 emission increases were mainly due to incrementally increasing coal and oil consumption, global decarbonization efforts and increased uses of low- or net-zero carbon energy are designed to reduce fossil fuel usage. This is significantly impacted by geopolitics and expense of energy sources and is highlighted by comparing countries of the OECD and non-OECD countries in future energy demand and source profiles. To summarize, fossil fuel usage is not likely to change, and is in fact predicted to increase by 2050 globally,[131] though the distribution of the use of these resources will shift substantially to developing economies.

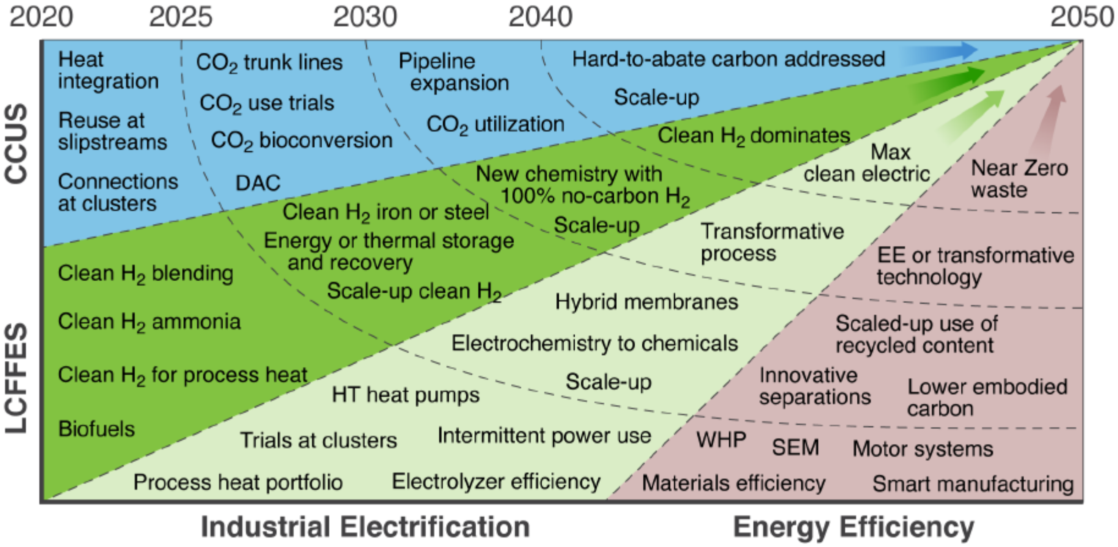
Non-OECD countries in Asia, Africa, and South America will have considerable impact on distribution of energy and heat sources as they add energy demand to their economies and industries. With the industrial sector responsible for a large part of greenhouse gases emissions worldwide and a significant share of industrial process relies on natural gas. Natural gas will play a significant role in reducing, but not necessarily eliminating carbon emissions of industries, and this to the extent that natural gas can economically displace coal and petroleum liquids.

To harness the potential of natural gas while minimizing its environmental impacts, collaboration among policymakers, industry stakeholders, and researchers is paramount. Supportive policies, investments in research and development, and a focus on decarbonization technologies, including CCUS, CCU, biogas, SNG, and low-carbon hydrogen production, are essential to successful integration into industrial decarbonization strategies. In the broader context of decarbonization policy and regulation, five main actions are needed: carbon pricing, financial incentives, research funding, emissions targets, and energy standards.

While these actions aim to decarbonize the industry sector and combat climate change, there is a legitimate concern about the potential for higher costs for energy-intensive industries and the risk of industrial relocation to countries with fewer regulations. Balancing the imperative of decarbonization with economic considerations remains a significant challenge that requires careful policy development and international cooperation.

In summary, the role of natural gas in industrial decarbonization is evolving, and its future depends on responsible management, technological advancements, and collaborative efforts. Achieving a sustainable industrial sector while mitigating climate change necessitates a balanced and comprehensive approach (Figure 35) that leverages the strengths of natural gas while addressing its environmental challenges and addresses the needs of developing nations to have access to reliable, inexpensive forms of power.

Figure 39. Landscape of major R&D investment opportunities for industrial decarbonization across all subsectors by decade and decarbonization pillar (U.S. DOE).



Note: Acronyms: DAC (direct air capture); EE (energy efficiency); HT (high temperature); SEM (strategic energy management); WHP (waste heat to power); LCFFES (Low Carbon Fuel for Energy Systems)

Source: U.S. DOE.

7.1. Recommendations and Next Steps

This paper is an initial assessment and provides a framework for continued analysis of industrial decarbonization. Overcoming the significant challenges to industrial decarbonization requires a various approach involving government incentives, research and development initiatives, and international cooperation. Below are some recommendations and solutions that can address these challenges.

- **Government Incentives and Funding**:

Although some countries, like the United States through the IRA or the EU through adoption of CBAM, have incentivized emissions reductions more countries should consider similar financial incentives such as tax credits, subsidies, and grants, to encourage the adoption of low-carbon technologies and the retrofitting of existing facilities. For example, governments can offer incentives to steel producers who invest in hydrogen-based direct reduction technologies or to cement manufacturers using carbon capture and utilization (CCU) processes.

The establishment of a carbon pricing mechanism, like a carbon tax or cap-and-trade system, can create economic incentives for companies to reduce emissions. The revenue generated from these mechanisms can be reinvested in R&D for low-carbon technologies or used to fund infrastructure for green energy.

- **Research and Development (R&D)**:

Governments, research institutions, and industry stakeholders should collaborate on R&D initiatives to develop and scale up innovative low-carbon technologies. For instance, R&D programs can focus on improving the efficiency and cost-effectiveness of CCUS processes.

Investment in basic research for breakthrough innovations is essential. For steel, this might include developing novel methods for iron ore reduction, while the cement industry could explore new clinkers with lower carbon footprints.

- **International Cooperation**:

International agreements and partnerships can facilitate technology transfer and knowledge sharing. For example, a global alliance for low-carbon steel production can enable the exchange of best practices and innovative solutions.

Harmonizing carbon pricing mechanisms and emissions standards across countries can create a level playing field for the steel and cement industries, ensuring that companies do not face competitive disadvantages in international markets due to varying regulations.

- **Strategic Infrastructure Development**:

Governments can invest in critical infrastructure for the production and distribution of low-carbon energy sources. For example, creating a network of hydrogen production and distribution facilities can support the transition to hydrogen-based steel production.

Establishing infrastructure for CCUS can be pivotal for the cement industry. Governments can provide funding and regulatory support for CCUS projects.

- **Resource Efficiency and Circular Economy**:

Policies should encourage resource efficiency and circular economy practices. Governments can incentivize the use of alternative raw materials in concrete production, such as recycled aggregates, fly ash, or slag. Eco-design principles can be integrated into building codes and standards to promote sustainable construction and minimize the demand for traditional cement.

- **Global Standardization**:

International organizations and governments can collaborate on developing global standards and best practices for low-carbon steel and cement production. This can help streamline processes and promote global competitiveness.

Many of these solutions and recommendations are already in place and allow the development of pilot projects cited. For example, the Uhas initiated several policies and programs to support the transition to a low-carbon steel and cement industry. The European Green Deal outlines the path to climate neutrality by 2050 and includes funding for R&D in low-carbon technologies. The EU initiated a phased transition away from providing free allowances under the ETS for the steel industry until 2034, gradually introducing the CBAM. These measures involve imposing tariffs on emissions-intensive products imported from regions with inadequate or nonexistent emissions regulations.

8. Acronyms

45Q: refers to 26 U.S. Code § 45Q on credit for carbon oxide sequestration
AEO: Annual Energy Outlook
AGI Acid Gas Injection
AGI: Acid Gas Injection
BCM: Billion cubic meters
BCMe: Billion cubic meters equivalent
BTU: British thermal units
CARB: California Air Resources Board
CarbonSAFE: Carbon Storage Assurance Facility Enterprise
CBAM: Carbon Border Adjustment Mechanism
CCS: Carbon Capture and Storage
CCU: Carbon Capture and Utilization
CCUS: Carbon Capture, Utilization, and Storage
CH4: Methane
CHP: combined heat and power
CNG compressed natural gas
CO: carbon monoxide
CO2: carbon dioxide
CO2e carbon dioxide equivalents
COP: Conference of the Parties
DOE: U.S. Department of Energy
EIA: U.S. Energy Information Administration
EOR: Enhanced Oil Recovery
EPA: Environmental Protection Agency (United States)
ETS: Emission Trading System
EV Electric Vehicles
FECM: Fossil Energy and Carbon Management (U.S. DOE)
FID: Final Investment Decisions
FLIGHT: Facility Level Information on Greenhouse Gases Tool
gCO2e: gram carbon dioxide equivalents
GHG greenhouse gas
GHGRP: GHG Reporting Program
Gt: Giga ton or ton
H2: hydrogen gas
H2S: Hydrogen Sulfide
IEA: International Energy Agency
IEEFA: Institute for Energy Economics and Financial Analysis
IEO: International Energy Outlook
IRA: Inflation Reduction Act of 2022
LCA: Life-Cycle Assessments
LCFS: Low Carbon Fuel Standard (California)
LNG: Liquefied Natural Gas
MENA: Middle East and North Africa
MITEI: Massachusetts Institute of Technology Energy Initiative
MJ: Mega Joule
MMBtu: Metric Million British Thermal Units
MMcf: million metric cubic feet
MRV: Monitoring, Reporting, and Verification
MT: metric ton or ton
Mtoe: million tons of oil equivalent
MVA: Monitoring, Verification, Accounting
MWh: megawatt-hour
NDC: Nationally Determined Contribution
NETL: National Energy Technology Laboratory
NG: natural gas
OECD: Organization for Economic Co-operation and Development
OPEC: Organization of the Petroleum Exporting Countries
PHMSA: Pipeline and Hazardous Materials Safety Administration
R&D: Research and Development
RD&D: Research, Development, and Demonstration
RNG: Renewable Natural Gas
SDWA: Safe Drinking Water Act
SMR: steam methane reforming
SNG synthetic natural gas
TAG: Treated Acid Gas
TBtu: trillion British thermal units
TCF: trillion cubic feet
Twh: Terawatt-hour
UIC: Underground Injection Control
UIC: Underground Injection Control
UNFCCC: United Nations Framework Convention on Climate Change
USDW: Underground Sources of Drinking Water
USGS: United States Geological Survey
WRI: World Resources Institute
WTI: West Texas Intermediate

9. Appendix

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