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The Impact of Energy-Intensive Industries on the Carbon Emissions : A Review

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ABSTRACT

Industrial de-carbonization is becoming a crucial part of climate mitigation initiatives due to the global shift to a low-carbon economy. Global warming is largely caused by greenhouse gas (GHG) emissions, primarily carbon dioxide (CO_2), which are produced by industrial sectors such as steel, cement, and petrochemicals. The emission profiles and decarburization paths of major industrial sectors are reviewed in this study, which also evaluates present effects and potential mitigation techniques. Although clinker manufacturing and combustion processes pose a problem to the cement industry, which accounts for around 8% of worldwide CO_2 emissions, the sector is working to reduce emissions through the use of carbon capture technology, energy efficiency, and supplemental cementitious materials (SCMs). In addition, the steel sector, which contributes between 7 and 9% of the world's CO2 emissions, is investigating switching from conventional blast furnaces to renewable energy-powered electric arc furnaces (EAFs), although obstacles like infrastructure and technical scalability still exist. Furthermore, despite technical breakthroughs, emissions from the petrochemical sector—particularly from plastics and fertilizers continue to rise. Promising emission reductions are provided by circular economy activities, such as chemical and mechanical recycling, as well as bio-based feedstocks. The article assesses the significance of key technologies, including electrification, energy efficiency enhancements, integration of renewable energy, carbon capture, use, and storage (CCUS), and material substitution through circular economy practices, in accelerating industrial de-carbonization. Despite the great promise of these breakthroughs, high capital costs, unclear policies, inadequate infrastructure, and inconsistent technological maturity prevent their widespread adoption. In order to encourage low carbon transitions, policy and regulatory frameworks such as international climate agreements, government subsidies, and emissions pricing are crucial. Finally, achieving net-zero emissions and meeting climate objectives by the middle of the century will require a multifaceted strategy that incorporates technical innovation, regulatory assistance, and systemic industry reform.

Keywords: Carbon, industry, decarburization, greenhouse gas.

Introduction

Innovation in low-carbon technologies has drawn more attention recently as a major force behind the low-carbon transition and economic decarbonisation. The industrial sector is a large producer of carbon emissions and a substantial contributor to economic development. Conventional manufacturing methods release significant amounts of greenhouse gases (GHGs) and rely mostly on fossil fuels. The greenhouse effect and global warming are caused by greenhouse gases or GHG gases, which are atmospheric gases that trap heat close to the Earth's surface, much like a greenhouse warms its interior. Nitrous oxide (N_2O), carbon dioxide (CO_2), methane (CH_4), and fluorinated gases such as sulfur hexafluoride (SF_6) and hydrofluorocarbons (HFCs) are important greenhouse gases[1-3]. Agwaidar et al. [4], investigate the evolution of greenhouse gas emissions in Libya from 1990 to 2020 by analyzing their sectoral distribution across the energy, industry, waste, and agriculture sectors and the contributions of key gases such as CO_2, CH_4, and N_2O. The results indicate that the energy sector is the important source of emissions, accounting for more than 90% of the total emissions, with carbon dioxide comprising 97.63% of this total. Industrial de-carbonization has emerged as a key element of climate strategy as nations commit to net-zero targets. CO_2 makes up 90% of industry's greenhouse gas output. Steel, cement, ethylene, and ammonia are the four industrial commodities that are responsible for half of industry's CO_2 emissions. The term "low carbon industry" describes industrial systems that use energy efficiency, greener energy sources, circular economy principles, and cutting-edge technology like carbon capture to drastically cut or eliminate carbon emissions. The peaking concentration levels, according to McKincey & Company, anticipate that CO_2 emissions in 2030 will be between 18 and 29 $GtCO_2$ as opposed to 36 GtCO21990, a decrease of between 20 to 50% throughout this time[5, 6]. In order to analyze the emission profiles of the main industrial sectors and evaluate both established and new decarbonisation solutions, this research synthesizes sector-specific issues and technology, emphasizing important routes and policy mechanisms for industrial decarbonisation.

1. Key Sectors Driving Industrial Emissions

1.1 Cement and Concrete

About 8% of human-caused carbon dioxide (CO_2) emissions come from the cement sector, making it a major contributor to global greenhouse gas (GHG) emissions. Between 2015 and 2020, the industry's emissions increased by 1.8% annually[7].Due to growing demands for new infrastructure and buildings, cement demand is expected to rise by almost 20% by 2050. This growth highlights the urgent need for the cement industry to implement efficient emission mitigation strategies in order to meet global climate goals, such as keeping temperature increases to 1.5 to 2 °C [8]. It has been reported that more than half of the output emissions are from the calcination process, which makes the production of Portland cement clinker the most carbon-intensive step in the cement manufacturing process[9, 10].The bulk of the remaining emissions are produced by fuel combustion for heating the kilns to high temperatures and for mining and transporting the materials as shown in Figure 1.

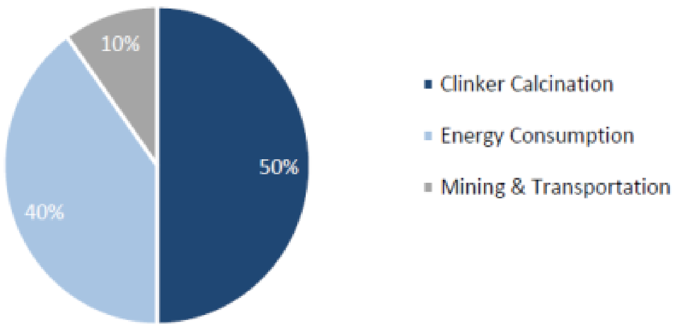

Figure 1. Emission sources for ordinary Portland cement production (Source: low carbon cement production issue paper, May 2022, USA)

One product of the pyroprocessing step of the cement-making process is clinker. In essence, it is a blend of limestone and additional raw materials that have been baked in a rotating kiln to temperature between 1400 and 1500°C. Clinker is the main component of OPC, the most popular kind of cement and the foundation for concrete, when it is finely ground and combined with gypsum[7]. The US's cement consumption and clinker production from 2010 to 2020 are depicted in Figure 2.

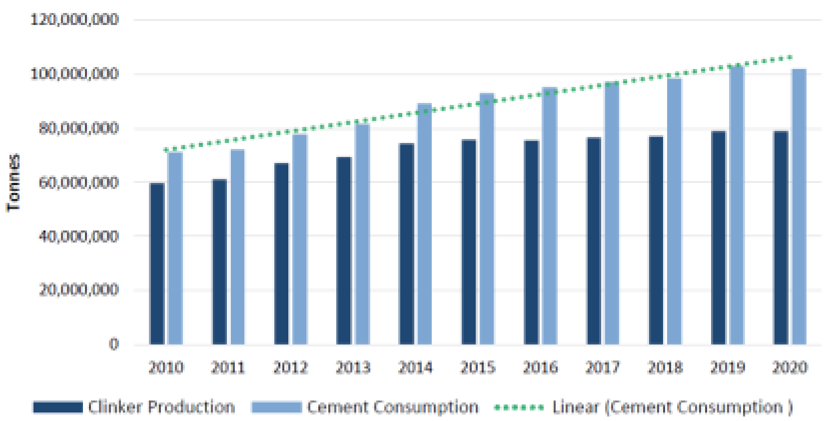

Figure 2. US Clinker Production & Cement Consumption: 2010 -2020 (Source: low carbon cement production issue paper, May 2022, USA)

The cement industry is exploring strategies to reduce emissions, including fuel switching, energy efficiency improvements, carbon capture, utilization, and storage, and product substitution. One key approach is replacing OPC with supplementary cementation materials (SCMs), which can improve concrete's workability and durability.

1.2 Steel and Metals

The steel industry plays a foundational role in the global economy and modern society. The steel industry's processes have significantly increased CO_2 emissions by 185% over the past three decades, primarily from fuel combustion and crude steel production[11, 12].Figure 3 shows global CO_2 emissions from crude steel production between 2000 and 2019, despite increased demand, with CO_2 emissions per ton decreasing due to energy efficiency and cleaner technologies, highlighting the challenge of decarbonizing the industry [11].

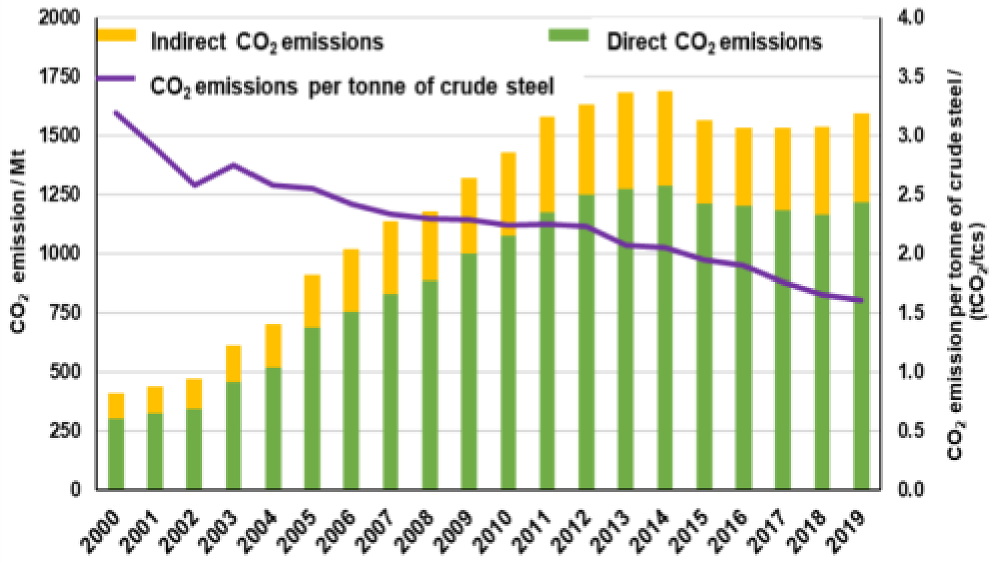

Figure 3. The global CO_2 emissions from crude steel production between 2000 and 2019, (Source: Low-Carbon Development for the Iron and Steel Industry in China and the World: Status Quo, Future Vision, and Key Actions)

Approximately 5% of CO_2 emissions in the EU and 7-9% of global emissions are caused by the iron and steel sector. To meet the climate targets set forth in the Paris Agreement and the EU 2030, the steel industry must decarbonize its production processes by more than 50%. [13]. It is clear that low-carbon steel manufacturing is crucial for de-carbonization in the metal industry. Implementing low-carbon processes can improve performance and reduce carbon footprint. 20% of steel production costs are energy-related, requiring renewable energy sources. 70% is produced in blast furnaces, 30% in EAFs, and has high recycling rates[14, 15].China is among the countries embracing the idea of achieving carbon neutrality and taking some measures in this regard, Figure 4 shows the key actions for the carbon neutrality in China by 2060.

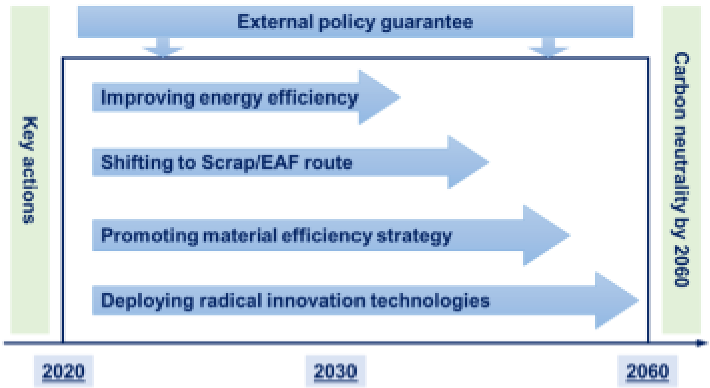

Figure 4. The key actions for the carbon neutrality in China by 2060, (Source: Low-Carbon Development for the Iron and Steel Industry in China and the World: Status Quo, Future Vision, and Key Actions Nov 2021, China)

The low-carbon steel industry faces major challenges including high upfront investments in hydrogen, CCS, and new technologies, along with uncertainty in scaling immature innovations. Infrastructure gaps like green hydrogen pipelines and renewable energy supply also hinder progress.

1.3 Chemicals and Petrochemicals

Petrochemicals, including plastics, rubber, and fertilizers, contribute significantly to global economy and oil demand. However, they have a significant climate impact, with direct CO_2 emissions growing by 41% between 2010 and 2020. To achieve net zero emissions by 2050, emissions need to decrease by 12% between 2020 and 2030[16]. The International Energy Agency predicts that petrochemicals will account for the majority of global oil demand growth through 2030, driven by rising demand for plastics and chemicals, especially in emerging markets[17].Unlike transportation (which can shift to electric vehicles or biofuels), petrochemical feed stocks are harder to decarbonizes and often rely on oil or gas based inputs.Petrochemical companies are utilizing bio-based feedstock and recycling processes to decarbonize their production, a practice that has been in place for a long time.

Aromatics and light olefins can be produced from bio-naphtha, which is a by-product of the process of renewable diesel or sustainable aviation fuel (SAF) production. Companies such as INEOS, ENI, and BASF are already producing bio-naphtha and are planning for more.Recycling and enhancing circularity plays a crucial role toward low carbon industry. As an example, plastic recycling is an area that has great potential for improvement because of current insufficient efforts.The OECD reports that only 9% of global plastic waste is recycled annually, and by 2060, it predicts a tripled global waste rate. This highlights the importance of ramping up recycling and building a circular plastics value chain[16].There are several ways to close the loop for the plastics value chain: reuse, mechanical recycling, and chemical recycling. Reusing means that a plastic product gets consumed again. Mechanical recycling refers to crushing and melting plastic and turning it into another product without changing the plastic's chemical composition. Mechanical recycling can work well with high quality plastic.The rapidly declining renewable cost is one main cause for the low cost estimation. Renewable energy supply solutions, in combination with electrification, account for 40% of total emissions reductions. Annual biomass use grows to 1.3 Giga tones; green hydrogen electrolyser capacity grows to 2435 G Watts and recycling rates increase six fold, while product demand is reduced by a third, compared to the reference case. CO_2 capture, storage and use equals 30% of the total decarburization effort (1.49 Giga tones per year), where about one-third of the captured CO_2 is of biogenic origin. Circular economy concepts, including recycling, account for 16%, while energy efficiency accounts for 12% of the decarburization needed. Achieving full decarburization in this sector will increase energy and feedstock costs by more than 35%. The analysis shows the importance of renewable based solutions, accounting for more than half of the total emissions reduction potential[18].

2. Technologies for Low Carbon Industry

As industries face increasing pressure to meet net-zero targets, the implementation of low carbon technologies is critical. This section outlines key technology categories and their applications relevance in heavy industries such as steel, cement, chemicals, and manufacturing.

2.1 Electrification

Electrification involves replacing fossil fuel based systems (e.g. gas burners, diesel boilers, etc,) with electric alternatives, ideally powered by renewable energy. It helps to cut both direct emissions (from fuel combustion) and indirect emissions (if the electricity comes from clean sources). Applications of electrification in industrial sector are represented in Table 1.

Table 1: Applications of electrification in industrial, (Source: EU climate targets: how to decarbonize the steel industry, EU science hub, European commission, Jun 2022)

Application area	Technology example	Replaces
Heating	Electric resistance heaters, induction heating, electric boilers	Gas/oil fired boilers
Steel making	Electric Arc Furnaces (EAF), plasma torches	Blast furnaces
Drying Processes	Microwave and infrared dryers	Steam / gas dryers
Mechanical Operations	Electric motors and pumps	Internal combustion engines
Low-Temp. Processing	Industrial heat pumps	Gas fired heating

2.2 Energy efficiency technologies

Energy efficiency remains one of the most cost-effective strategies for decarbonization. Several key technologies support this goal, such as advanced Process Control (APC) enables real-time process optimization by using digital sensors and control systems. In addition, waste heat recovery captures thermal energy from exhaust streams and repurposes it for preheating or power generation can be support it as well. Furthermore, high Efficiency motors and drives help reduce energy loss during mechanical operations, while Variable Speed Drives (VSDs) optimize motor performance by adjusting their operations to match actual load requirements, thereby minimizing unnecessary energy consumption[19, 20].

2.3 Renewable Energy Integration

Industrial decarbonization relies heavily on shifting the energy supply from fossil fuels to renewable sources. Key technologies supporting this transition include solar photovoltaic (PV) systems and wind turbines, which can directly power industrial equipment and facilities. Solar thermal heating is used in processes such as pre-heating, drying, and steam generation across various sectors. Battery energy storage systems enhance power reliability and help balance energy loads. Additionally, green hydrogen serves as a clean fuel alternative for high-temperature industrial processes and the production of synthetic fuels [21, 22].

2.4 Carbon Capture, Utilization, and Storage (CCUS)

One of the most important sets of technologies for decarbonizing heavy industry is Carbon Capture, Utilization, and Storage (CCUS). It includes absorbing carbon dioxide (CO_2) from the atmosphere or from industrial operations, using the CO_2 in a variety of goods like concrete, chemicals, and fuels, or storing it underground in geological formations for a long time [23, 24]. In hard-to-abate industries like steel, cement, and chemicals, where CO_2 emissions come from both the burning of fossil fuels and natural chemical processes, like the calcination process in cement production, CCUS is essential to lowering direct emissions.

2.5 Circular Economy and Material Substitution

A circular industrial model reduces resource extraction and waste generation. Recycling, reusing materials, and developing alternatives (e.g. green concrete, bio-based plastics) are highly effective to achieve the carbon neutrality. Table 2 includes some innovations that support the circular economy.

Table 2: Some circular economy innovations, (Source: EU climate targets: how to decarbonize the steel industry, EU science hub, European commission, Jun 2022.)

Innovation	Application
Scrap Recycling	Especially in steel, aluminum, and plastics
Chemical Recycling	Breaks down polymers into their original monomers
Clinker Substitution	Replaces a portion of cement clinker with fly ash or calcined clay
Industrial Symbiosis	Collaborations between industries to share resources, waste, or energy.
Bio-based Feed-stocks	**Such as bio-naphtha in petrochemicals or biomass in cement kilns**

3. Policy and Regulatory Frameworks

The shift to a low carbon industrial economy requires more than just technological innovation. It demands a strong and coherent policy and regulatory environment. Governments and international bodies play a critical role in setting emissions standards, establishing carbon pricing, and funding clean technology deployment. These frameworks define the emission limits, taxes, best practices and influence how industries invest, operate, and innovate toward sustainability.

4. Challenges to De-carbonization

Despite growing momentum toward net-zero goals, several structural and systemic challenges continue to hinder the de-carbonization of industry such as the capital cost, infrastructure gaps, policy uncertainty and technology readiness.

5. Conclusion

Industrial de-carbonization is crucial for achieving global climate targets and requires a systemic shift across high-emission sectors like cement, steel, and petrochemicals. Challenges include high implementation costs, infrastructure gaps, and policy uncertainty. Coordination among governments, industries, and research institutions is essential for accelerating low carbon innovation. Future work should focus on developing low carbon emission strategies in Libya's industrial sector, balancing industrial growth with sustainability objectives. Long-term resilience through innovation, regional adaptation, and equitable transitions is crucial for a low carbon industrial economy.

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