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Review

Charting the Course: Navigating Decarbonisation Pathways in Greece, Germany, The Netherlands, and Spain's Industrial Sectors

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Abstract: In the quest for a sustainable future, energy-intensive industries (EIIs) stand at the forefront of Europe's decarbonisation mission. Despite their significant emissions footprint, the path to comprehensive decarbonisation remains elusive at EU and national levels. This study scrutinises key sectors such as non-ferrous metals, steel, cement, lime, chemicals, fertilisers, ceramics, and glass. It maps out their current environmental impact and potential for mitigation through innovative strategies. The analysis spans across Spain, Greece, Germany, and the Netherlands, highlighting sector-specific ecosystems and the technological breakthroughs shaping them. It addresses the urgency for the industry-wide adoption of electrification, the utilisation of green hydrogen, biomass, bio-based or synthetic fuels, and the deployment of carbon capture utilisation and storage to ensure a smooth transition. Investment decisions in EIIs will depend on predictable economic and regulatory landscapes. This analysis discusses the risks associated with continued investment in high-emission technologies, which may lead to premature decommissioning and significant economic repercussions. It presents a dichotomy: invest in climate-neutral technologies now or face the closure and offshoring of operations later, with consequences for employment. This open discussion concludes that while the technology for near-complete climate neutrality in EIIs exists and is rapidly advancing, the higher costs compared to conventional methods pose a significant barrier. Without the ability to pass these costs to consumers, the adoption of such technologies is stifled. Therefore, it calls for decisive political commitment to support the industry's transition, ensuring a greener, more resilient future for Europe's industrial backbone.

Keywords: energy-intensive industries; decarbonisation technologies; sector-specific analysis; economic and regulatory frameworks

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1. Introduction

The European Union's new Climate Law aligns closely with the Paris Agreement (PA). It incorporates the new PA Article 6 and sets an ambitious target for 2030: a reduction in CO_2 emissions by at least 55% compared to the 1990 levels [1]. Additionally, the European

Climate Law commits the EU to an innovative goal: achieving carbon neutrality by 2050 [2]. Energy-intensive industries (EIIs) are at the forefront of this European leading decarbonisation strategy vision [3]. Yet, no holistic decarbonisation strategy has been developed at both the EU and country level.

An EII's ecosystem includes a wide range of sectors, i.e., non-ferrous metals, steel, aluminium, chemicals, fertilisers, cement, ceramics, lime, glass, paper and pulp. These sectors are characterised by a high energy intensity and are responsible for a large share of greenhouse gas (GHG) emissions produced mainly due to fuel combustion, electricity production, and process emissions (Figure 1). Several decarbonisation actions can be applied for all these sectors, such as the capture, utilisation, and storage (CCUS) of process emissions, the use of renewable energy technologies for electricity production instead of fossil fuels, and the increase in carbon-neutral fuels in the fuel mix [4,5]. The zero-carbon transition of EIIs by embracing climate-friendly practices will not only be beneficial for the environment but also will ensure the individual company's long-term competitiveness [6]. Nevertheless, many sectors have already peaked in their efforts to reduce their GHG emissions without fulfilling their targets [7]. In this regard, innovative solutions are necessary to transform the way these sectors operate. The current manuscript describes EII's ecosystems across different sectors, focusing on four exemplary European countries, i.e., Spain, Greece, Germany, and the Netherlands. Specific technological innovations are summarised, whereas challenges for the widespread utilisation and potential measures are elaborated. For the sake of completeness, it is important to acknowledge that other sectors like the petrochemical industry also require decarbonisation solutions, such as hydrocarbon fuel conversion. However, this review focuses specifically on decarbonisation options for energy-intensive sectors like non-ferrous metals, cement and lime, chemicals and fertilisers, ceramics, glass, and steel. The petrochemical sector, while significant, falls outside the scope of this manuscript. For instance, a recent study explores innovative methods for hydrogen production, which could be relevant for decarbonising the petrochemical industry [8].

While this manuscript does not delve into detailed statistical analysis or projections, it aims to reflect the status of decarbonisation innovations within multiple sectors. The insights presented are based on consultations with industry representatives, stakeholders, and technology providers, offering a qualitative perspective on the current state and future prospects of decarbonisation efforts in energy-intensive industries (EIIs).

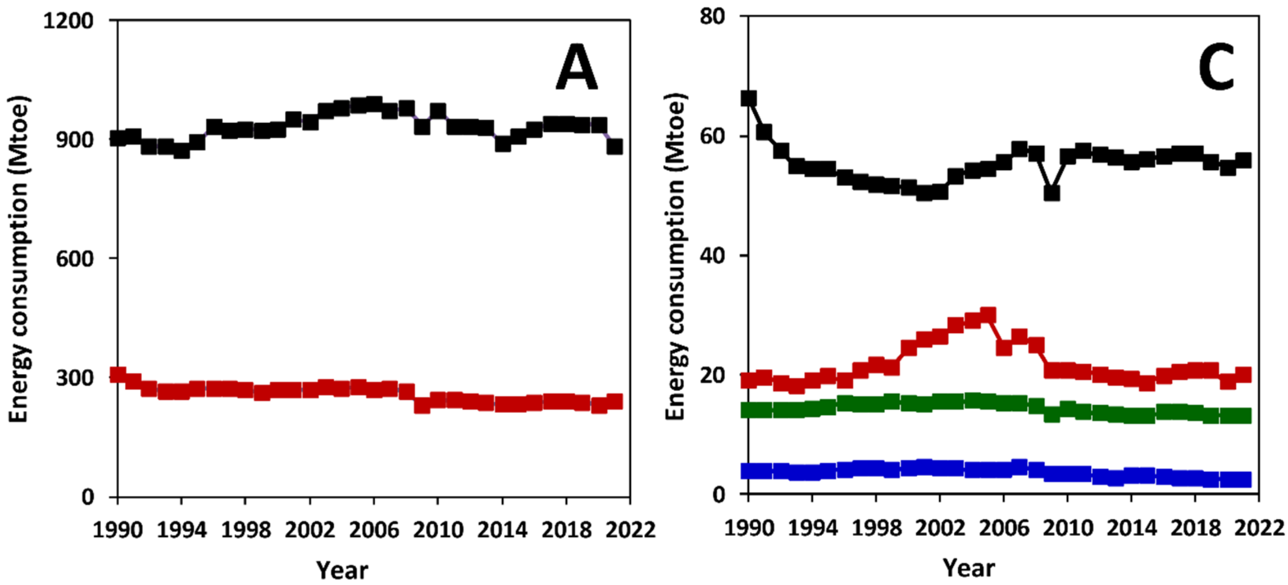

Figure 1. *Cont.*

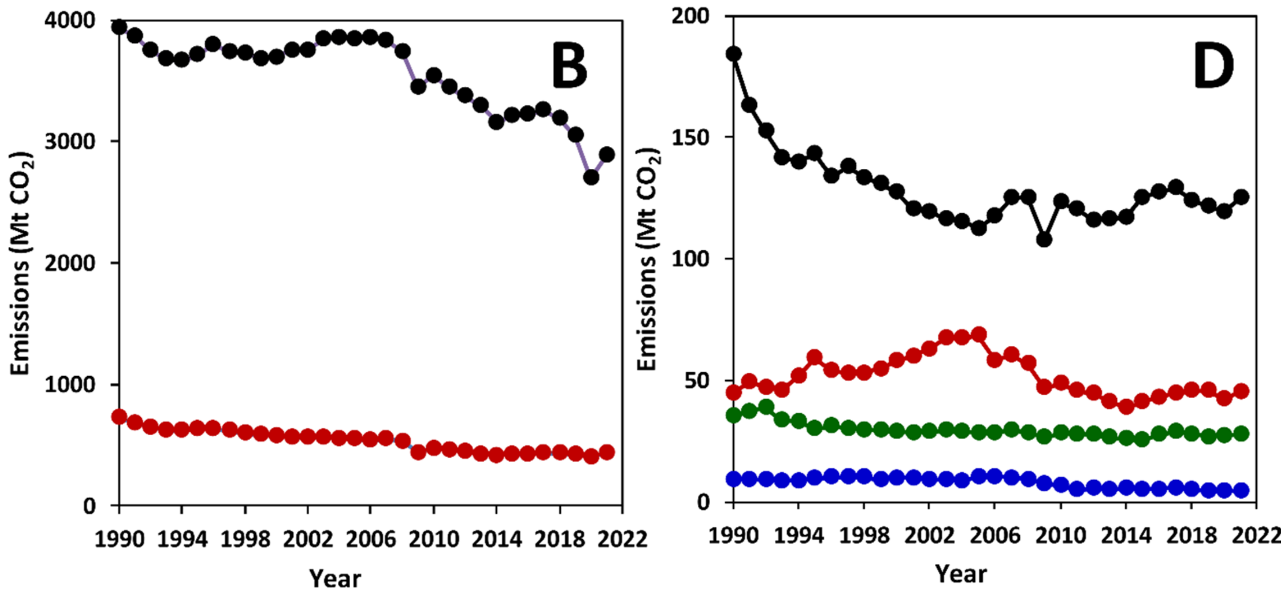

Figure 1. Energy consumption and CO_2 emissions in Europe. (**A**) Total energy consumption in the EU (black) and by its EIIs (red); (**B**) Total CO_2 emissions in the EU (black) and by its EIIs (red); (**C**) Disaggregated energy consumption by EIIs in Greece (blue), Spain (red), the Netherlands (green), and Germany (black); and (**D**) disaggregated CO_2 emissions by EIIs in Greece (blue), Spain (red), the Netherlands (green), and Germany (black) [9].

2. Methodology

2.1. Overall Literature Analysis Approach

This review was prepared as part of a European-funded project RE4Industry aimed at providing an overall understanding of the main energy-intensive industry (EII) sectors in Europe, including non-ferrous metals, steel, cement, non-metallic minerals, ceramic and glass, and chemical industries. A comprehensive literature search was conducted using multiple academic databases, focusing on peer-reviewed articles mainly published between 2010 and 2022. The inclusion criteria were studies that specifically addressed decarbonisation strategies for energy-intensive industries within the European context, as well as those focusing on the selected countries: Spain, Germany, the Netherlands, and Greece. Exclusion criteria involved omitting articles that did not provide empirical data or detailed analysis of decarbonisation options.

This review aimed to synthesise findings from those studies to provide a comprehensive overview of current and emerging decarbonisation strategies, highlighting regional differences and commonalities. Individual reports for each sector were produced, following a common structure that included the status of the sector in the EU, an overview of the technology processes employed, potential alternatives for cleaner processes, well-established practices for renewable energy integration and CO_2 emission reduction, additional measures for transitioning to a decarbonised, circular economy model, and opportunities and barriers for decarbonisation. Feedback for drafting the individual sector reports was collected from expert consultations, direct visits to national organisations, and a survey of the literature. This methodological approach ensured a focused and relevant selection of the literature, providing a robust foundation for the review's conclusions.

2.2. Country Selection

The selection of Spain, Greece, the Netherlands, and Germany for this review is based on their diverse and representative profiles within the European context of energy-intensive industries (EIIs). These countries were chosen to provide a comprehensive overview of the decarbonisation challenges and opportunities across different regions and industrial landscapes in Europe. Spain is a significant player in the European EIIs sector, particularly in the steel, cement, and ceramics industries. Its geographical location and climatic conditions also present unique challenges and opportunities for renewable energy integration and decarbonisation efforts. Greece represents the southern European region, with a strong presence in the cement and non-metallic minerals sectors. The country's economic structure and recent efforts towards energy transition make it a valuable case study for understanding the barriers and drivers of decarbonisation in similar economies. The Netherlands is a key hub for the chemical and petrochemical industries in Europe. Its advanced technological infrastructure and proactive policies towards sustainability provide insights into the potential for innovation and the implementation of cleaner processes in EIIs. Germany is one of the largest industrial economies in Europe, with a significant presence in the steel, chemical, and non-ferrous metals sectors. Germany's leadership in renewable energy adoption and its ambitious climate goals make it a critical case for examining the intersection of industrial activity and decarbonisation strategies. By focusing on these four countries, the review captures a broad spectrum of industrial activities, regulatory environments, and regional characteristics. This selection ensures that the findings and recommendations are relevant and applicable to a wide range of contexts within the European Union, thereby providing a robust foundation for understanding the status and future pathways for decarbonising energy-intensive industries in Europe.

3. Status of EIIs in Four Representative European Economies

Industrial emissions are roughly divided between fuel combustion for process heat (52 percent) and greenhouse gases (GHGs) released during chemical reactions in feedstock processing (48 percent), such as natural gas processing for ammonia production or iron ore preparation for steelmaking [10]. Process emissions also include fugitive GHG emissions, such as methane leakage from natural gas pipelines. The industrial sector can be categorised based on production techniques and the types of GHGs emitted. Heavy industry, which accounts for 46 percent of industrial emissions, includes segments like non-metallic minerals, metals, and base chemicals. These segments produce basic products such as cement, glass, steel, and plastics, requiring high temperatures. For instance, blast furnaces for steelmaking reach 1800 °C, and kilns for limestone calcination to produce cement exceed 1600 °C. Nearly half of the emissions in these segments are CO_2 process emissions, necessitating changes in feedstock and production processes to eliminate them. Oil, gas, and mining contribute to 19 percent of industrial emissions, with about 25 percent from methane leakage, primarily from natural gas pipelines. Most CO_2 emissions in this sector arise from the heat needed for petroleum cracking and distillation, which requires temperatures up to 400 °C.

In Spain, the EII sector is one of the most important industrial activities [11]. EIIs account for around 60% of the total energy consumption in the country (Figure 2). Amongst the different industrial sectors, the one with the highest energy consumption is the one focused on goods production like chemicals (14%), iron and steel (15%), non-ferrous metals—including alloys—(13%), oil refining (8%), and paper and pulp (6%).

Currently, almost all of the energy required for EIIs is provided by non-renewable sources, such as coal, oil, and natural gas. Electricity plays a key role as well (ca. 22.6%), but renewable energies have a minor presence in the industrial energy landscape, with a share of less than 7%. It is worth mentioning that Spain follows the EU emission reduction target with an objective set by the Spanish government to reduce greenhouse gas (GHG) emissions by 23% by 2030, taking as a reference the year 1990. Unfortunately, sectorial emission targets have yet not been specified at the national level, except for the cement sector, which has set a decarbonisation roadmap [12].

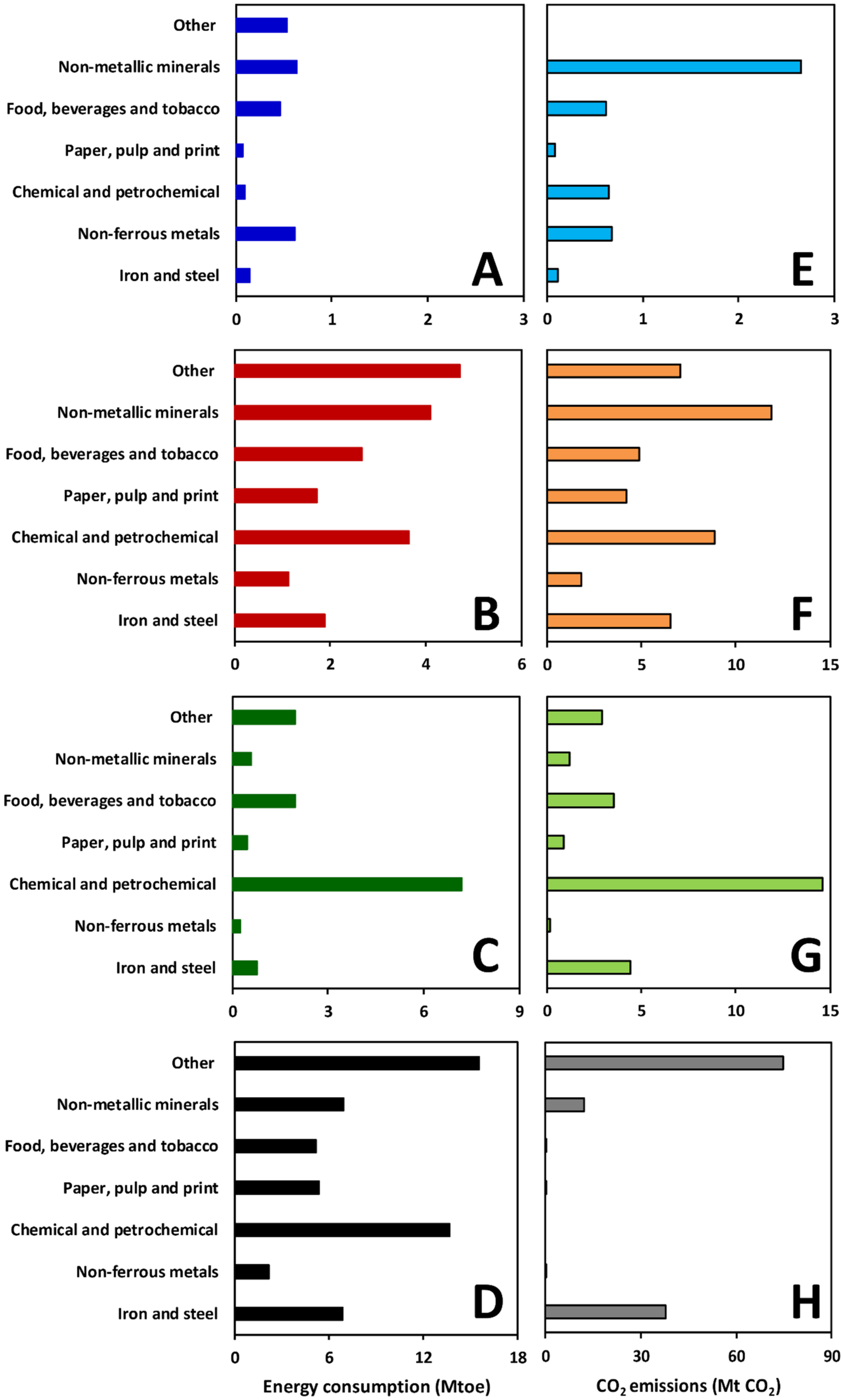

Figure 2. Disaggregated industrial energy consumption (**A**–**D**) and EU-ETS CO_2 emissions (**E**–**H**) of Greece (dark blue and light blue bars), Spain (dark red and orange bars), the Netherlands (dark green and light green bars), and Germany (black and grey bars) in 2021.

The intrinsic characteristics of EIIs make them difficult to decarbonise. Primary production process equipment is characterised by high initial investment costs and is designed with a very long service life, e.g., up to 50 years in the case of cement plants [13]. The industry has made numerous efforts in the past, mainly due to its own need to maintain its economic competitiveness (and thus reduce the energy and CO_2 costs associated with its activity). However, due to the characteristics of EIIs, they still account for a significant amount of national energy.

Greece is not as heavily industrialised as other EU member states; however, there is a significant presence and economic activity of several large EIIs, as well as several smaller companies. In some specific sectors or subsectors, the activity of Greek companies is relevant, even on the EU level. The power and heat sectors are responsible for the largest share of the GHG emissions in Greece. Interestingly, these sectors have been able to reduce their emissions by almost half since 2015 (Figure 1). Within the primary goods production sectors, the aluminium (1415 Kt of CO_2eq in 2022) and cement (4543 Kt of CO_2eq in 2022) sectors are the largest GHG emission contributors [9]. The ceramic industry is responsible for the largest increase in GHG emissions in recent years. However, it is also worth noting that the ceramic sector has significantly decreased its CO_2 emissions since 2005.

In the period from 2008 to 2010, there has been a large fall in the CO_2 emissions of the cement industry. This might be explained by the economic crisis faced by Greece during those years, which significantly weakened the construction industry and consequently reduced the cement production in the country and therefore the reduction in emissions.

Even though Germany has by far the highest share of industrial production in the EU, the energy intensity of its industrial sector is lower than the European average [14]. According to Eurostat, in the fiscal year of 2018, within the EU-27 economic landscape, Germany emerged as the predominant contributor to value added across several key industrial sectors. Specifically, it accounted for 33.4% of the manufacturing sector's value added. Concurrently, Germany's employment figures mirrored this dominance, representing 27.2% of the EU-27 workforce in manufacturing [15]. These statistics underscore Germany's integral role in the industrial and utility sectors within the European Union. Every job in energy-intensive basic production secures about two jobs in other branches of industry and in the service sector. That means that EIIs generate about 2.5 million jobs in Germany [16].

In Germany, the industry consumes over one-fourth of the nation's energy, while energy-intensive industrial sectors accounted for about 77% of the total energy used in 2021, with the chemical and metal industries being the primary consumers. Other sectors with high energy usage include the production of coke, petroleum products, glass, ceramics, and paper products. Natural gas stands out as the primary energy source in the German industry, serving not only as a fuel but also as a crucial raw material, particularly within the chemical sector [14].

EIIs in Germany spend more than 17 billion euros on energy every year, for a net electricity consumption of 525 TWh [17]. Figure 2 shows Germany's disaggregated industrial energy consumption and European Emissions Trade System (EU-ETS) CO_2 emissions. The iron and steel industry accounts for the largest share of industrial emissions at around 28%, followed by refineries (20%), cement clinker production (18%), and the chemical industry (15%).

In parallel to the energy consumed by its industry, German EIIs invest heavily in energy-saving and emission-reducing production technologies. Between 1990 and 2012, EIIs reduced their GHG emissions by a total of 31%, while increasing production by 42%. In 2020, emissions fell in most of the industrial sectors compared to 2019.

The Dutch industry is responsible for 31% of the total final energy consumption in the Netherlands [18]. The chemical and pharmaceutical industries combined account for more than half (53%) of the total final energy consumption within the industry. Other sectors with relatively high final energy consumption include building materials, steel, and food and beverage industries (Figure 2). In 2022, the overall energy consumption of the industry saw a downward trend as opposed to 2021 (i.e., 10.9%). This was influenced by energy efficiency measures and the increase in energy prices, as well as the reduced growth in industrial activities thanks to natural gas and oil as the primary energy sources for the Dutch industry which serves both as fuel and as raw material, mostly for the chemical industry [19].

In terms of GHG emissions, the power and heat sectors are the major contributors within the Dutch EU Emission Trading System (EU-ETS). However, they have reduced their emissions by 17.32 Mton (or 34%) since 2015 (Figure 1). Within the sectors focused on in this paper, the other-chemicals (9.25 Mton CO_2-eq in 2020, ferrous metals (5.80 Mton) and fertiliser industry (5.07 Mton) are the largest contributors (Figure 2). The fertiliser industry is responsible for the largest increase in GHG emissions in the period from 2005 to 2015, though these emissions stabilised from 2015 onwards. The large decrease in the emissions in the cement industry is directly related to the closure of the ENCI Maastricht plant that produced Portland clinker from its own marl mine [20].

The chemicals and fertiliser industries are both the largest energy-consuming and GHG-emitting industries in the Netherlands. The three largest chemical companies are Chemelot (Sittart Geleen), Shell Nederland (Moerdijk), and Dow Benelux B.V. (Hoek). Together, they are responsible for 83% of the total GHG emissions (7.7 Mton) in the chemicals industry. Yara Sluiskil is the largest company specialising in fertiliser production and is responsible for 65% (3.3 Mton) of the total GHG emissions in the fertiliser industry, followed by Chemelot with 35% (1.8 Mton). The ferrous metals industry also shows a significant share in total GHG emissions, of which 99.7% derives from Tata Steel Ijmuiden. The remaining 0.3% comes from FN Steel, a relatively small player specialising in steel wires.

A summary of CO_2 emissions of the above-mentioned countries is presented in Figure 2. As can be seen, the highest producer is Germany, followed by Spain, then the Netherlands, and Greece being the least important producer. All these countries, however, should apply a combination of multiple decarbonisation actions (i.e., renewable energies (RES) along with carbon capture, use, and storage (CCUS) technologies) to reduce their GHG emissions under the 2030 EU targets.

4. Decarbonisation Actions across Different Sectors

Several decarbonisation actions can be applied across different sectors in order to achieve a clean energy transition [21]. In a broader context, these could be divided into specific actions implemented across the whole industry.

Electrification refers to the transition of heat generation processes in EIIs to operate exclusively on green electricity [22]. As the power supply increasingly relies on renewable energy sources and becomes greenhouse gas-neutral, substantial emissions reductions can be achieved on a large scale.

The use of bio or synthetic fuels primarily consists of replacing fossil fuels, for example, with biomass or greenhouse gas-neutral synthetic gases [23]. It should be noted that even if the use of biomass or bioenergy is generally a comparatively inexpensive and very effective option, the availability of biomass is limited. Biomass is also seen as a solution in other areas (e.g., residential heating, shipping, and aviation) to achieve climate neutrality. This raises the question of how to deal with scarcity and finite resources [24,25].

The use of carbon capture utilisation (CCU) or carbon capture storage (CCS) consists of separating CO_2 from the exhaust gases of certain plants or from the air and then supplying it as a feedstock to other processes, or alternatively to store it. CCU and CCS could become essential in some sectors where there is a high percentage of unavoidable process-related emissions (e.g., lime, cement) [26]. The integration of advanced technologies such as photothermal co-catalytic reduction in CO_2 to value-added chemicals can significantly enhance the potential of carbon capture utilisation (CCU) in industry decarbonisation efforts [27].

The use of hydrogen also plays an important role as a clean energy source [28]. The aim in the near future is to produce hydrogen in a greenhouse gas-neutral manner, for example, through water electrolysis based on electricity from renewable sources. This renewable concept corresponds to Power to X (PtX) technologies, a key future of the energy transition [29].

Hydrogen production, although crucial for various applications, still predominantly relies on natural gas, resulting in associated CO_2 emissions. However, research is actively being conducted to find alternative approaches to improve its efficiency, such as enhancing recycling processes. This becomes particularly significant in energy- and resource-intensive sectors like the steel industry.

In addition to the strategies mentioned, recent research highlights several innovative approaches to decarbonising energy-intensive industries. The synergy of carbon capture, waste heat recovery, and hydrogen production presents a promising pathway for industrial decarbonisation. The integration of Calcium Looping (CaL) for CO_2 capture and methane dry reforming (MDR) for hydrogen production can enhance the efficiency and sustainability of industrial processes [30]. In the European context, the deployment of hydrogen and carbon capture utilisation and storage (CCUS) technologies is crucial for achieving net-zero emissions. However, this transition faces several challenges, including technological barriers and potential inequitable impacts on communities [31]. The iron and steel industry, with its high electricity consumption, offers substantial potential for demand response strategies. The adoption of hydrogen-based direct reduction in iron and electric arc furnace technology (H2-DRI-EAF) can significantly reduce electricity costs and enhance flexibility in energy use [32]. Finally, the cement and concrete industry must adopt a multifaceted approach to decarbonisation, incorporating alternative clinker technologies, carbon capture and storage, and improved energy efficiency. Policy interventions, collaboration, and the adoption of circular economy principles are essential to overcome the challenges and achieve sustainable development [33].

4.1. Decarbonisation Actions for the Non-Ferrous Metals Industry

The non-ferrous metals industry is making efforts to transition to a world where societies rely on clean, renewable sources of energy by 2050. Non-ferrous metals are essential for many of the widely known low-carbon projects, like hybrid, electric, and fuel cell vehicles, solar panels, wind turbines, and thermal systems. Future demand for these metals is expected to increase in the near future as demonstrated by recent studies [34]. The demand for rare-earth elements (REEs) has markedly risen, as evidenced by the fact that, on average, each person in 2018 utilised approximately 12 times more REEs than in 1956 [35].

The sector has been making progress in terms of reducing its emissions over the past few decades [36]. It has been especially successful in reducing direct and indirect GHG emissions by 60% since the 90s. The non-ferrous metal industry has fully embraced circular economy-related initiatives by achieving high and progressive recycling rates, as described in the Table 1. Although the industry is highly electro-intensive, it has reduced its indirect greenhouse gas emissions significantly, through the increasing decarbonisation and renewable energy uptake in the European power sector. On the other hand, this points out that the non-ferrous metals industry is extremely sensitive to electricity prices, which affects its economic performance and competitiveness.

In the context of the energy transition and the pursuit of carbon neutrality, a strategic focus on renewable energy sources becomes imperative. By designing European policies that promote renewables, a fertile environment for long-term contracts could be established. Power Purchase Agreements (PPAs) could play a crucial role in managing energy price volatility. Notably, PPAs might facilitate stable access to renewable electricity at predictable prices. To fully leverage their potential, a robust regulatory framework for PPAs and long-term power contracts is essential, particularly for electro-intensive industries.

Table 1. Prospective technologies and pilot applications within the EU non-ferrous metal industry subsectors.

Subsector	Prospective Technologies and Pilot Applications
Aluminium	i. Wettable cathodes to the molten aluminium pad. The potential energy savings are estimated at up to 15–20% [37] ii. Inert anodes: energy savings are estimated at up to 10–30% [37,38] iii. Lower electrolysis temperature to around melting point. Savings could be around 5% [39] iv. High-temperature carbothermic reduction of alumina: 20–30% more efficient compared to electrolysis [40] v. Chloride process [41] vi. Kaolin as raw material in aluminium production could be a more efficient process by 12–46% [37] vii. Carbon capture storage (CCS) technologies [42] viii. Karmøy Technology Pilot Plant, a new hydro-developed technology uses 15% less energy [43]
Copper	i. The oxygen flash technique at TRL 8, which allows for more efficient copper smelting [37] ii. Copper extraction using electrolysis is a new low-TRL metal production method via molten electrolysis [37] iii. Alternative fuels, like hydrogen or biofuels [44] iv. Waste heat recovery—Aurubis: heating extraction by copper smelting by-products [45] v. Carbon capture storage (CCU) technologies
Silicon and ferroalloys	i. Organic Rankine Cycle: transforming waste heat into electricity ii. Carbon capture and utilisation (CCU): The Algae Project of Finnfjord AS [46] iii. Carbon capture storage (CCS)
Nickel	i. Electrification of various processes is considered as a long-term potential solution
Zinc	i. Electrification of melting furnaces ii. Carbon capture storage (CCS) technologies [47]

The European non-ferrous metals industry, in its pursuit of greener practices, must address the carbon footprint associated with its heat requirements. Already, several key steps have been taken, including substituting coal with natural gas, implementing combined heat and power production, and recovering waste heat through energy efficiency measures. However, achieving further emissions reduction presents complexities. Industry stakeholders must carefully evaluate various options that are currently available or will attain a high Technology Readiness Level (TRL) in the future. These options include further electrification, green hydrogen utilisation, renewable gases as substitutes for natural gas, and leveraging biomass and bioenergy.

4.2. Decarbonisation of the Cement and Lime Industry

Cement and lime industries are both of great importance to the EU's economy. Construction and civil engineering require cement products, while the steel sector also needs lime for the production of building supplies, paints, plastics, and rubber. For these industries, environmental sustainability is of utmost significance, and innovation involves the utilisation of waste as a substitute for raw materials and fuels [48].

The European lime industry has taken several actions in order to reduce GHGs. Fuel savings is achieved by up-scaling energy efficiency. Since 2010, the European Lime industry has made efforts to reduce emissions related to the calcination step of the process. It is estimated that by building new vertical kilns and retrofitting the existing ones, the industry could achieve 16% fuel reduction by 2050 [49]. As an example, the new vertical PFRK kilns are considered nowadays to be the most energy-efficient ones. Apart from these, energy heat recovery from waste during the exothermal reaction of hydration could be used in drying limestone, in the milling process, or in heating buildings and producing electricity.

Fuel switching by lower carbon alternatives like wood powder firing, biomass gasification, methanol, turpentine and tall oil could aid in the decarbonisation of the sector. Lignin could also be used as fuel in lime production. Recently, the future use of hydrogen has been considered a very promising alternative [50]. Waste could be used as a fuel. However, one must take into consideration that not all types of kilns can process all types of waste [51]. This can be a cost-effective solution in relation to the transport costs and unit prices of those fuels [52]. Hydrogen production using alkaline electrolysis is another developing technology. Since 70% of the total lime CO_2 emissions are produced during the reaction stage capturing, CO_2 could be a sustainable yet not economical alternative in decarbonising the lime industry [53].

It is noteworthy that the energy usage costs constitute 50–60% of the total production expenses for the European cement industry. Thermal energy accounts for about 20–25% of the cement production cost. The most energy-intensive phase of the value chain is at the cement plant, where two critical materials are produced: clinker and cement. Cement production is a 24/7 process and is naturally energy-intensive. Concrete on the contrary is a construction material with one of the lowest energy and carbon content. However, the manufacturing of its key component, cement, is CO_2-intensive.

Carbon neutrality along the cement, concrete and clinker value chain requires the deployment of existing and new technologies. In Table 2, a selection of decarbonisation technologies is presented.

Table 2. Decarbonisation innovations in the cement industry.

Cement Industry Materials	Emissions Reductions Measurements
Clinker: its chemical process causes 60–65% of cement manufacturing emissions	• Alternative decarbonated raw materials like waste materials and by-products from other industries • Fuel substitution with alternative locally available biomass fuels [54] • Thermal efficiency kilns through converting preheater and other kiln types to pre-calciner kilns and by recovering heat from the cooler to generate up to 20% of the electricity needed for the cement plant [55] • New types of cement C=clinkers can result in 20–30% CO_2 savings • Carbon capture utilisation and storage (CCUS) could fully eliminate its process emissions and potentially result in the future delivery of carbon-negative concrete [49]
Cement: use of low ratio clinker cement or even alternatives to decrease emissions related to cement itself	• Low-clinker cement: in 2021, 21% of the total substitutes are natural pozzolans, limestone, or burnt oil shale and non-traditional substitutes such as calcined clay and silica [56]
Concrete	• Transitioning from small-scale, on-site concrete batching using bagged cement to industrialised processes, coupled with data-driven calculations of material requirements, results in substantial CO_2 emission reductions

Ultimately, reducing carbon emissions from electricity usage is crucial to the decarbonisation efforts within the cement industry. The use of renewable electricity will result in zero emissions when used in clinker, cement, and concrete production [57].

4.3. Decarbonisation of the Chemical and Fertiliser Industry

The chemical industry has a crucial role in Europe's transformation to a more energy-efficient and low-carbon future. In these directions, the sector has already made significant steps and has reduced its GHG emissions. Further decarbonisation potentials need to be implemented in order to fully decarbonise the sector. Deep emissions reduction in Europe is technically possible through power supply decarbonisation and CCS integration within chemical processes in the 2030–2050 timeframe [58].

Table 3 summarises a range of current and future technologies that could sustain Europe's track record of energy and emissions intensity improvements. Final energy demand could be maintained at a constant level, and emissions could be virtually suppressed with energy efficiency (33% of the total emissions reductions), CCS (25%), renewable electricity (20%), fuel switching, and measures to reduce nitrous oxide emissions (22%). To enable continuous and competitive production, access to the required amounts of affordable and reliable energy and feedstock will be necessary. This will be a complete and challenging transition for renewable energy production [59].

Table 3. Potential decarbonisation solutions within the ethylene, methanol, and chlorine chemical subsectors.

Ethylene:	The production process for low-carbon ethylene relies on methanol production from hydrogen and CO_2, followed by the methanol-to-olefin (MTO) process. While the methanol-to-olefin process is currently in commercial use, operational facilities are primarily situated in China, with none of these plants operating in Europe thus far [60].
Methanol:	In conventional methanol production, the hydrogenation of CO_2 serves to fine-tune the CO/H_2 ratio in the syngas by introducing small amounts of CO_2. The synthesis of methanol from both CO and CO_2 is interconnected through the water–gas shift reaction. Electrochemically converting CO_2 directly into methanol, where the reduction occurs at the cathode and is paired with oxygen evolution at the anode, represents a highly promising strategy for making methanol production more sustainable by integrating renewable energy as the electricity supply [61].
Chlorine:	The transition could involve converting mercury cell plants to membrane cell technology, shifting from monopolar to bipolar membrane technology, and retrofitting membrane cell plants that were operational in 2010 with oxygen-depolarised cathodes [62].

The utilisation of feedstock plays a crucial role in both fossil fuel and biomass consumption within the chemical industry. To mitigate greenhouse gas (GHG) emissions, two key strategies are essential: the efficient utilisation of existing feedstock and the exploration of alternative feedstock options. Leveraging renewable resources, including biomass and recycling, is vital [63]. Additionally, incorporating secondary feedstock from industrial and post-consumer waste streams, along with innovative alternatives like CO_2 capture and utilisation, contributes to a more sustainable approach.

The utilisation of captured carbon as feedstock encompasses a wide array of processes, involving its incorporation into product fabrication or synthesis. The energy required for these processes must be generated in a "carbon-free" manner to prevent additional CO_2 emissions during energy production.

Carbon capture and utilisation (CCU) can be developed symbiotically with carbon capture and storage (CCS). If investments are made in pipeline infrastructure for CCS, these pipelines could also serve as a feed infrastructure for CCU applications. Simultaneously, the storage functionality provided by CCS ensures optimal utilisation of CCU-based plants [64].

On the other hand, CCU has the potential to accelerate advancements in capturing technologies, enhance the public acceptance of CCS, and serve as an alternative in regions where CO_2 storage is not feasible. It is important to note that the investment cost of CCS is high, and its attractiveness depends on the volume of captured CO_2. In general, the larger the volumes of captured CO_2, the more cost-effective all steps of CCS become [65].

In summary, achieving the decarbonisation of the EU chemical industry is a multifaceted challenge, with solutions varying across different chemical sectors. However, significant strides and substantial CO_2 emission reductions should be realised, particularly in the production of fertilisers, which are both high-volume and carbon-intensive. Two key strategies emerge as pivotal game-changers.

Hydrogen plays a critical role in ammonia and methanol production. While hydrogen generation is energy-intensive, transitioning to renewable energy sources for hydrogen production could markedly reduce fossil fuel use and the GHG footprint. Electrolytic water cleavage, despite its GHG-saving potential, currently faces economic challenges due to higher costs compared to gas steam reforming [66].

Biomass utilisation offers several benefits. It reduces dependence on fossil fuels, major GHG emitters in chemical processing. Biomass absorbs CO_2 during growth, offsetting emissions during manufacturing or even disposal. Biomass sources are renewable, in contrast to finite fossil fuels, which are likely to exhibit greater price volatility in the future. Considering that nearly 75% of total European fertiliser production consists of nitrogen-based fertilisers, it becomes evident that ammonia plays a dominant role. In 2020, ammonia production accounted for 30 Mt out of the total 35 Mt of greenhouse gas emissions generated by the fertiliser industry. Ammonia production is carried out in two stages, the steam methane reforming (SMR) stage for the production of hydrogen, which is the feed material of hydrogen production and the Haber–Bosch stage where hydrogen produced and nitrogen react, producing ammonia [67].

The average energy efficiency for European fertiliser production plants is higher than the global average due to the use of relatively modern technology and the reduced use of coal as the main energy supply. The main driver for this is Europe's strict environmental legislation that has pushed the European industry in the past few years to invest steadily in order to increase its efficiency and reduce GHG emissions [68]. As a consequence of these innovative advancements in technology, the European fertiliser industry's ammonia plants are among the most energy efficient worldwide, with the lowest GHG emissions, even though the production of nitrogen fertilisers, which reaches 75% of the total production, is characterised by high carbon intensity. On average, 1.9 t of CO_2 is released on-site during the production of one ton of ammonia during the conventional method [69].

Over the past few decades, the European fertiliser industry has made significant strides in enhancing the energy efficiency of its production processes. However, the chemical industry finds itself at a juncture where additional investments in existing technology are unlikely to yield substantial gains. To drive meaningful progress, the fertiliser industry must embark on a journey of reinvention, pushing beyond the boundaries of current technology [70].

Despite significant progress in reducing emissions, the chemical industry's current production methods remain energy-intensive. Specifically, steam methane reforming, while the least carbon-intensive, still generates substantial CO_2 [71]. In the SMR process, ammonia—the foundation for all mineral nitrogen fertilisers—is produced, serving as a vital link between atmospheric nitrogen and nearly half of our food supply. Approximately 70% of ammonia is used for fertilisers, while the remainder finds applications in plastics, explosives, and synthetic fibres. Ammonia plays an indispensable role in global agriculture, but its production relies on fossil fuels, primarily natural gas. Currently, global ammonia production accounts for approximately 2% (8.6 EJ) of total final energy consumption [72].

4.4. Decarbonisation of the Ceramics Industry

Over the past few decades, the European ceramic sector has made significant strides in energy efficiency. Innovations in kiln designs and drying techniques have led to more efficient processes. Notably, the drying and firing stages have transitioned into continuous processes, resulting in a stable energy demand. However, achieving net-zero (fuel) CO_2 emissions requires further decarbonisation efforts [73].

The Royal Dutch Building Ceramics Association has developed a comprehensive "Technology Roadmap". Although this roadmap outlines various strategies for the energy transition within the ceramic industry in the Netherlands, due to the similarity of the ceramics industry within Europe, the described decarbonisation alternatives might also apply to other countries within the region [74].

Green gas, also known as biomethane, offers a direct replacement for natural gas in ceramics production. It can be produced through anaerobic digestion or gasification. Anaerobic digestion suits wet biomass, while gasification is more effective for dryer biomass. By integrating green gas into the gas grid, ceramic plants can seamlessly decarbonise their production process by substituting natural gas with this environmentally friendly alternative [75].

Hydrogen presents another fuel substitution option. However, its applicability depends on kiln design and necessitates burner modifications. Firing ceramics with hydrogen leads to higher temperatures and increased NOx emissions. Further research is essential to fully assess its impact on product quality [50].

Renewable electricity has the potential to replace natural gas in kilns and drying processes. Although smaller-scale pottery kilns already utilise electric heating, implementing electric furnace kilns on a large, continuous scale (such as tunnel kilns) remains unproven. Additionally, electrification significantly increases on-site electricity consumption, which may pose challenges in rural areas where ceramic plants are typically located [22].

Simulations comparing electric drying with hydrogen and natural gas drying indicate that electric drying is the most efficient in terms of air usage and reduced flue gas losses. However, scaling up electric kilns to meet the demands of large ceramic plants presents significant challenges [74].

The concept of an extended tunnel kiln emerged in the Netherlands around 2010. This innovative approach involves extending the length of conventional tunnel kilns by up to 50%.

Besides the decarbonisation measures mentioned above for the ceramics sector, Table 4 shows some emerging technologies for making ceramic manufacturing more sustainable.

Table 4. Emerging technologies for making ceramic manufacturing more sustainable.

Technology	Benefits	Energy and/or Emissions Reductions
Microwave-assisted drying and firing	By using microwave heating, energy is delivered more efficiently to dry and fire products [74].	Significant reductions in energy end use of around 99%
Hybrid kiln	Instead of employing a sulphurised kiln and dryer, exhaust gases are supplemented through a gas-driven heat pump to enhance thermal energy [76].	This option can deliver up to 65% in energy savings
Heat pipe heat exchanger	Heat pipe heat exchanger applied to a ceramic kiln employing exhaust gases to preheat water delivered energy recovery rates of about 15% [74].	Energy savings could reach up to 65%

Table 4. *Cont.*

Technology	Benefits	Energy and/or Emissions Reductions
Controlled dehumidification	The water that is condensed within the chamber releases heat that is supplied in the drying process.	This system is entirely closed; therefore, the energy savings can be as high as 80%
Heat recovery facilities in dryers	Heat recovery enables the drying air to be replaced with hotter gases from other manufacturing processes [77].	Such gases can come from cogeneration engines or the kiln and help mitigate emissions between 57 and 73% and energy savings ranging from 60 to 80%
Kiln cars and furniture with low thermal mass	The use of thermal mass in kiln cars helps in reducing the thermal energy requirement for the heating of supporting refractories.	This technique reduces running costs, repairs, and maintenance and leads to fuel savings of up to 70%

4.5. Decarbonisation of the Glass Industry

The glass manufacturing industry currently prioritises identifying enablers, barriers, and technical options to decarbonise various stages of production (Table 5). One critical process shared across most glass manufacturing methods is the initial melting of glass [78]. The glass manufacturing industry faces the critical challenge of reducing its carbon footprint. At the heart of this endeavour lies the raw material melting process, where various materials—such as sand, minerals, and recycled glass—are meticulously mixed and charged into high-temperature furnaces (typically operating around 1500 °C). The resulting molten glass is then shaped and allowed to cool. Importantly, all subsectors within the glass industry converge during the glass-melting step, making innovations in this phase applicable across the board [79].

Beyond the furnace, attention turns to combustion and flue gases. Fuels—whether gaseous, liquid, or solid—are combusted alongside oxidants (such as air or oxygen). These processes yield flue gases and CO_2 emissions from batch materials, which are systematically collected and withdrawn through dedicated flue gas channels. To achieve a closed CO_2 circuit loop, technologies like cooling traps and baghouse filters are employed to separate CO_2 from other gaseous components and solid particles [80]. Waste heat recovery emerges as a straightforward yet effective strategy. By harnessing the exhaust heat from furnace gases, manufacturers can reduce their carbon footprint. This recovered heat finds applications in other high-temperature processes or can be integrated into local district heating grids [81].

Electric power remains indispensable throughout glass manufacturing. The adoption of renewable, CO_2-neutral energy sources—such as electricity—holds promise for further decarbonisation. Glass melting furnaces, often utilising electric power for electric boosting or hybrid operation modes, play a pivotal role in this transition [82]. Innovative technologies, including carbon capture and use (CCU) with hydrogen, represent the cutting edge of decarbonisation efforts. By embracing these strategies and maintaining a holistic approach that combines process optimisation and technological advancements, the glass industry can contribute significantly to a more sustainable and environmentally friendly future.

Table 5. Decarbonisation technologies within the glass sector.

Novel technologies	• Energy efficiency improvements in terms of fuel furnace consumption • Waste heat recovery to preheat combustion air and raw materials, or electricity cogeneration
Combustion innovations	• Oxifuel combustion [83] • Introduction of liquid biofuels (biodiesel and hydrotreated vegetable oil) [84]
Reduce combustion emissions	• Electric arc furnaces (EAFs) rather than gas-fired furnaces [13] • Hybrid furnaces running on multiple fuels and electricity • Study of feasibility of hydrogen to run glass furnaces [79]
Circularity	• Increased cullet use to produce new glass (the waste-to-material approach) [85] • Calcined raw materials such as CaO to substitute carbonates, reducing CO_2 emissions [86] • Carbon capture, utilisation, and storage [87]

4.6. Decarbonisation of the Steel Industry

The European steel industrial sector faces significant pressure due to its CO_2 emissions, which result from energy-intensive processes. This sector contributes approximately to 4% of total European CO_2 emissions and 22% of total EU industrial emissions [88]. Steel production in Europe primarily occurs through two routes. The primary route involves processing iron ore to produce iron sinter or pellets, which are then melted in a blast furnace with coke to create pig iron. It is further processed in a basic oxygen furnace to produce steel. The secondary route, on the other hand, relies on scrap metal and an electric arc furnace (EAF) to produce steel. While the primary route emits mainly direct greenhouse gases, the secondary route emits indirect greenhouse gases, which depend on the electricity mix used in the EAF. Consequently, reducing emissions in the sector primarily targets the primary route [89].

In 2020, the European steel sector supported over 2.6 million full-time equivalent jobs, with crude steel production reaching 139 million tonnes. The gross value added of the European steel industry was EUR 132 billion, considering direct, indirect, and induced effects. The EU sector consumed approximately 0.84 EJ of energy in 2020. Decarbonisation options are available for both routes of steel production [89].

To lower emissions, the primary route—being the highest CO_2 emitter—requires targeted measures (Table 6). These include methods like coke dry quenching, optimising pellet ratios, and implementing top gas recovery turbines in blast furnaces. Additionally, replacing coke with biomass and natural gas with hydrogen can significantly reduce CO_2 emissions during primary steelmaking. Injecting hydrogen or ammonia into the blast furnace to partially replace pulverised coal is another viable approach [90].

Lowering emissions from the secondary route involves optimising electricity usage in EAFs or transitioning toward renewable energy sources. However, many proposed solutions necessitate substantial amounts of affordable green electricity for iron ore pre-processing, H_2 electrolysers, furnaces, and electrolysis to achieve carbon neutrality. These energy sources are currently not cost-competitive compared to coke (excluding carbon tax) and will require further development [91].

To achieve the necessary drastic reductions, a transformative approach to ironmaking is essential, with several promising industrial-scale methods that avoid CO_2 emissions. The shift toward a low-carbon world necessitates a transformation in iron and steel production. There is no single solution for CO_2-free steelmaking; instead, a diverse portfolio of technological options must be considered, either individually or in combination based on local conditions. These technologies fall into four broad categories: biomass, carbon, hydrogen, and electricity. Furthermore, numerous projects within these categories are currently under development worldwide [32].

Table 6. Decarbonisation technologies within the steel sector.

Hydrogen	CCS	Electrolysis	Biomass
-Commercial e-H_2 as the primary reducing agent expected by the mid-2030s [92] -By 2050, the highest demand for e-H_2 in steel production will be in India and China [93] -All existing hydrogen applications will necessitate 3600 TWh	-By 2070, it is estimated that 75% of all CO_2 produced globally in iron and steel production can be captured -To achieve this, 10 steel plants with CO_2 capture capacity need to be built annually every year through to 2070	-In 2020, over 1800 million tons (Mt) of steel were produced globally [94] -A typical blast furnace (BF) can produce in the order of 2.5 Mt of iron per year -Today, kilograms of iron are being manufactured using electrolysis [95]	-Robust supply chains are required to make large amounts of biomass available to the industry [96]

5. Challenges for EIIs in Europe

Companies will not make the necessary replacement investments if the long-term economic and regulatory conditions are uncertain [97]. In light of increasing demands for climate protection, reinvesting in conventional, emission-intensive technologies faces a greater likelihood of being decommissioned early, increasing the risk associated with such endeavours. From the standpoint of companies as a rational economic actor, there are only two options: to invest in climate-neutral technologies in the next investment cycle, or to close existing production plants at the end of their service lives and, if necessary, make new investments abroad, thus triggering massive job losses (also known as the carbon leakage phenomenon) [98].

As illustrated above, technological potentials that could be harnessed to make the EIIs almost completely climate-neutral already exist today (or they are rapidly developing). But these technologies and production processes are still significantly more expensive today than conventional manufacturing processes, and the additional costs cannot be passed on to customers because of fierce international competition. Therefore, to stimulate investment in these innovations now, industry actors need political signals that the government will actively support this transformation.

A recent study analyses the drivers of industrial decarbonisation, and these can be grouped into the following four areas [99]:

- The importance of international, European, and national policies, such as the Paris Agreement and the EU ETS that set ambitious targets for GHG emissions reduction.
- Carbon pricing, including taxes and cap-and-trade systems, is highlighted as a critical economic tool for incentivising emission reductions, particularly in Europe, which has successfully implemented CO_2 taxes since 1991 in some EU countries.
- Energy efficiency measures are also crucial, with directives like the amended EED setting targets for improved energy efficiency by 2030.
- Lastly, RD&D and technology support are identified as essential for promoting low-carbon technologies and avoiding carbon leakage, with funding programs like the EU's Innovation Fund supporting this transition.
- Collectively, these drivers underscore the need for comprehensive policy support to achieve long-term climate goals and industrial competitiveness.

5.1. The Case of Spain

In the context of Spain, significant challenges in the decarbonisation of energy-intensive industries have been identified. The development of specific regulations for the use of by-products as feedstock is underway, addressing legal complexities associated with the utilisation and transportation of secondary raw materials. Certain residues are currently excluded from use due to non-compliance with existing waste legislation [100].

Electricity production alternatives, including nuclear power alongside renewable sources, are being considered to enhance the national energy mix. Consequently, the operational lifespan of nuclear power plants is being extended to ensure a stable electricity supply [101].

Community engagement initiatives have led to the creation of certifications for green products, aiming to raise awareness and encourage the production of circular, value-added goods and services. It is imperative that authorities provide greater recognition to EIIs that implement decarbonisation measures within their operations [102].

The transition to green energy will introduce new costs for EIIs, exemplified by the logistical challenges of green hydrogen transportation. Uncertainty prevails regarding the adaptability of existing natural gas infrastructure for future green hydrogen delivery to industrial sites. Such infrastructure is crucial for supporting additional projects, such as biofuel production, essential for industrial decarbonisation. Ensuring a consistent supply of alternative fuels, particularly those derived from by-products or waste (e.g., biomass, biogas), presents a substantial challenge for EIIs requiring large quantities [103].

Anticipated within the decarbonisation strategy is the potential saturation of electrical connection points within the grid. This necessitates investment in new distribution systems to manage increased electricity transactions. Furthermore, innovative financing mechanisms are essential to support the energy transition, including the integration of technologies into existing facilities through retrofitting, which may not always be straightforward [104].

5.2. The Case of the Netherlands

Achieving the goals of the Climate Agreement and the further transition to an emission-free economy in 2050 require a significant expansion of the energy infrastructure. Realising this in a timely manner is complicated. Industrial companies, network operators, energy producers and regional governments have jointly drawn up Cluster Energy Strategies (CESs) in 2021, covering five specific areas with existing industrial clusters, while the sixth is related to various sectors located throughout the Netherlands [105]. These CESs are further governed by the National Infrastructure Programme for Sustainable Industry and the multi-year programme infrastructure energy and climate MIEK [106].

Hydrogen and electrification play a major role in the decarbonisation plans of the Dutch industry. Both options depend strongly on the availability of large volumes of renewable electricity. The renewable electricity capacity planned to be produced on land is elaborated in the 30 Regional Energy Strategies (RESs) [107]. The RESs are expected to result in 35 TWh/year of renewable electricity production by 2030. However, most renewable electricity will have to be produced by wind parks at sea. According to the Climate Agreement, wind parks at sea with a joint capacity of 11 GW will produce 49 TWh/year by 2030 [108]. Given that in 2021 the capacity of wind at sea reached 2.5 GW and is expected to grow to 4.5 GW by 2030, a large effort still has to be made. The 35 TWh of renewable electricity on land plus 49 TWh of wind at sea as foreseen in the Dutch Climate Agreement of 2019 add up to 84 TWh of renewable electricity. This amount is well below the 128 TWh needed by the industry according to the Cluster Energy Strategies. Therefore, the advisory board "Additional Effort" as well as "Roadmap Electrification Industry" indicated that 45 TWh/year of additional renewable electricity should be available by 2030, meaning that about 10 GW extra capacity of wind at sea should be realised, plus additional infrastructure to bring the electricity (or hydrogen if already converted at sea) to the (mainly industrial) users.

5.3. The Case of Germany

Germany is one of the world's leading industrial locations. More than seven million employees in the manufacturing sector generate a fifth of the national value added. With the energy transition, Germany is pursuing an ambitious energy and climate policy [109].

As part of the Paris climate agreement, Germany committed itself to take steps to limit global warming to 1.5 °C, and national commitments pledge an emissions reduction of 65 percent compared to 1990 levels by 2030 and climate neutrality by 2045.

With the industrial sector being responsible for a fifth of Germany's greenhouse gas emissions (and with EIIs generating the biggest share of these emissions), the decarbonisation of the sector is key to achieving the long-term goal of greenhouse gas neutrality. In recent decades, the German industry has already made great progress in reducing greenhouse gas emissions and reduced its greenhouse gas emissions by a third between 1990 and 2018, without losing its strong position on the world market. More than that, the industrial sector has committed to reducing emissions by around 56 million tons (around 29 per cent) by 2030 (compared to 2018 levels) [110].

Nevertheless, further efforts still have to be made in order to achieve these objectives. Consequently, these cannot be achieved solely through further increases in energy efficiency. Over the last ten years, the industrial sector has increased its efficiency, but without achieving a corresponding reduction in emissions. Rather, fundamental changes in production processes will be necessary.

However, there are two big impediments to these fundamental changes. First, about one-third of emissions from EIIs take the form of process-related emissions, which cannot be avoided using conventional production techniques due to the raw materials used and to the associated chemical reactions. A study carried out by the Federal Ministry for Economic Affairs and Climate Action demonstrates that the transformation of industry is technically possible [111]. The study concludes that challenges are great, because industrial production processes that have been tested and applied over decades have to be fundamentally changed, and because almost all of the emission-avoiding technologies are associated with high additional costs [112]. The second big challenge faced by German EIIs in their decarbonisation commitments lies in the fact that capital-intensive production plants have long operational lifespans (often with depreciation periods of 50 to 70 years). This means that in the coming investment cycle, renewed investment in conventional technologies could lead to stranded assets, i.e., to the early decommissioning of assets that have not yet been fully depreciated, and to the associated economic losses. The situation faced by EIIs in Germany is alarming in this respect. In order to maintain current production levels, massive reinvestments into production plants will have to be made in the coming years. Some examples include the following: by 2030, around 53 per cent of the blast furnaces in the steel industry, around 59 per cent of the steam crackers in the basic chemical industry, and roughly 30 per cent of the cement kilns in the cement industry will need a reinvestment.

5.4. The Case of Greece

Greek EIIs face structural challenges with high electricity prices, influenced by market organisation. Under the Renewable Energy Directive and the NECP, Greece aims for a 35% RES share in energy consumption by 2030, requiring at least 9 GW of renewable power plants. The growth of variable renewable energy sources necessitates flexible power systems, with 23 flexibility options being evaluated for the Greek power grid to optimise renewable energy integration and potentially expand renewable PPAs [113].

While the cost of generating electricity from renewable sources is progressively declining, often becoming comparable to that of fossil fuels, the variable nature of wind and solar power necessitates the inclusion of additional shaping and firming expenses. These costs must be factored into the procurement strategies for renewable electricity, as they represent supplementary risks for energy-intensive industries (EIIs).

In order to solve this issue, the "Green Pool" concept has been proposed in a study commissioned by Mytilineos, a key player in Greece's industrial sector, consuming approximately 2.8 TWh of electricity annually for primary aluminium production, with a capacity exceeding 190,000 tons of aluminium [114]. The Green Pool concept envisions energy-intensive industries (EIIs) investing in new renewable energy capacities. The electricity generated is collectively managed through the Green Pool, optimising shaping and firming costs. EIIs receive renewable electricity proportional to their investment in the pool. Any residual shaping and firming costs may be offset by the Recovery and Resilience Facility funds. The Greek government has embraced the Green Pool, forming the foundation of a proposal to support the country's EII sector. However, as of October 2023, the European Commission has rejected the Green Pool proposal, citing concerns over its compatibility with EU competition rules, which has led to significant disappointment among Greek industrial stakeholders looking to reduce energy costs and transition to renewable sources [115].

On the one hand, the recent price hikes of both natural gas and CO_2 are actually a driver for decarbonisation all over Europe. On the other hand, EIIs are highly sensitive to energy costs and such increases can often make them stop production altogether rather than switching to new alternatives. Significant social opposition against several renewable energy projects in Greece has often been detected [116]. This opposition most strongly materialises against wind farms that have been set for establishment in mountainous and/or touristic areas of Greece. To the authors' knowledge, this activity has not directly impacted renewable electricity projects that have been planned with the explicit purpose of decarbonising the electricity supply of EIIs in Greece. More specific to the EII sector is the social opposition to initiatives related to the utilisation of alternative, waste-derived fuels in the cement industry. The opposition is more evident in the Volos cement plant, due to its close proximity to a big population centre and local air emission issues [117]. It should be noted that such issues are common in waste-to-energy projects in most countries of the world [118]. Moreover, it would appear that there is less opposition to plans related to the utilisation of "green waste" fractions, such as urban pruning, or other biomass assortments originating from post-fire forest management activities [119].

It should be noted that many Greek EIIs are actually small- or medium-sized companies, with limited capacities to implement investments related to renewable energy uptake. On the other hand, it is evident that Greek companies with a strong position in their sectors are in fact willing to implement investments related to the increased uptake of renewable energy.

6. Political Measures and Policy Instruments

While the above technological measures discussed in the present manuscript are important prerequisites, by themselves they cannot ensure the success of the transformation required by the industry in Europe. Additional political measures and policy instruments are needed to encourage the shift to a low-carbon production process, as those previously discussed somewhere else (Table 7). These can be grouped into broad categories based on their objectives and mechanisms.

Table 7. Policy instruments for climate-neutral industry. Information adapted from original source [120].

Market-Based Instruments	**Regulatory Instruments**
A. Carbon Pricing Mechanisms: • Carbon price floor with border carbon adjustment. • Carbon Contract for Difference (CfD). • Carbon price on end products.	C. Demand Creation and Standards: • Green public procurement. • Quota for low-carbon materials. • Green hydrogen quota. • Changes in construction and product standards. • Standards for recyclable products.
B. Financial and Investment Incentives: • Green financing instruments. • Climate surcharge on end products (as it serves to refinance other instruments).	

Market-based instruments include a carbon price floor with border adjustments. Carbon Contracts for Difference (CfD) and end-product carbon pricing seek to incentivise emission reductions through economic signals. Financial incentives such as green financing instruments and climate surcharges on materials aim to lower investment barriers in low-carbon technologies. Regulatory strategies encompass green public procurement and quotas for low-carbon materials and green hydrogen, as well as revised construction and product standards, and recyclability standards for products, all designed to create demand for sustainable materials and practices, ensuring a transition towards a low-carbon economy. Collectively, these instruments seek to establish a predictable market environment that encourages investment in and adoption of low-carbon technologies, while also fostering innovation and global leadership in green technology markets [120].

6.1. Financing and Investments

One of the main obstacles to the energy transition is the financing associated with the establishment and development of renewable projects. To achieve the EU's objective of becoming climate-neutral by 2050, substantial investments are required from both the public and private sectors. The European Commission predicts that the European economy needs to double its level of climate investments to deliver the EU 2030 targets [121].

Various tools have been developed to support sustainable investments, including the European Green Deal Investment Plan, which aims to raise at least EUR 1 trillion over the next decade [122]. The Just Transition Mechanism offers tailored financial and practical assistance to regions and industries significantly impacted by the transition [123]. This mechanism includes the Just Transition Fund, a dedicated transition scheme under Invest EU, and loans facilitated by the European Investment Bank. Additionally, the Innovation Fund and Horizon Europe provide substantial funding for low-carbon technologies and broader research initiatives [124]. Despite these opportunities, the complexity and diversity of funding mechanisms can be challenging, particularly for smaller entities. Simplifying administrative procedures for obtaining European funding would encourage the uptake of renewables and facilitate the industrial transition. Moreover, attracting private funding requires minimising investment risks, which is heavily dependent on maintaining a stable and predictable regulatory framework.

6.2. Barriers to Overcome and Possible Solutions

Several barriers hinder the decarbonisation of energy-intensive industries. Legislative misalignment often results in ineffective policies due to a disconnect between industrial needs and political legislation. Collaborative frameworks involving industrial stakeholders are essential to develop suitable regulations that support carbon neutrality without compromising global competitiveness [125]. Continued subsidies for fossil fuels divert funds from renewable energy development, so redirecting these subsidies towards renewables would accelerate the transition [126]. The financial burden of adopting zero-carbon technologies can be prohibitive, necessitating robust financing schemes to support industries in this transition. Additionally, industries fear losing competitiveness to regions with less stringent decarbonisation targets, making it crucial to ensure the availability of renewable fuels and facilitate access to biomass feedstock [127]. Technological and logistical challenges, such as storing green electricity and managing biomass logistics, present significant hurdles that require innovative solutions like advanced battery technologies [128]. Lastly, the absence of a level playing field and insufficient incentives can deter industries from adopting renewable technologies. Designing products for recyclability from the outset can help recover valuable materials and reduce consumption, further supporting the transition to a low-carbon economy.

7. Conclusions

Energy-intensive industries (EIIs) are pivotal in Europe's ambitious decarbonisation agenda, given their substantial contribution to overall emissions. Despite this, a comprehensive decarbonisation strategy at both the EU and national levels remains ambiguous. While numerous sectors have initiated efforts to curtail their greenhouse gas (GHG) emissions, they have yet to meet their established objectives. Consequently, pioneering solutions are needed.

The sectors under scrutiny in this analysis were the non-ferrous metals, steel, cement, lime, chemicals, fertilisers, ceramics, and glass. This manuscript not only delineated the current state of each sector but also catalogued an extensive array of decarbonisation strategies that could mitigate their environmental impact.

Furthermore, this manuscript described the EII ecosystems across diverse sectors, with a particular focus on four exemplary European countries: Spain, Greece, Germany, and the Netherlands. The document has reported specific technological innovations and discussed the challenges impeding their widespread adoption, alongside potential remedial measures. A suite of decarbonisation strategies is applicable across various sectors to facilitate a seamless energy transition. Broadly, these strategies can be categorised into industry-wide implementations such as electrification, the utilisation of green hydrogen, biomass, bio or synthetic fuels, and the deployment of carbon capture utilisation and storage.

The willingness of companies to invest in replacement technologies will depend on stable long-term economic and regulatory frameworks. Meanwhile, reinvestments in traditional, highly emitting technologies are increasingly likely to face premature decommissioning, thereby amplifying the associated risks. From a corporate perspective, the rational economic choices are twofold: either invest in climate-neutral technologies in the forthcoming investment cycle or shutter existing facilities upon reaching the end of their operational lifespan, potentially relocating investments overseas and precipitating significant job losses.

As discussed, the technological capabilities to accomplish EIIs nearly entirely climate-neutral are not only available but also evolving swiftly. However, these decarbonisation technologies and processes currently incur costs markedly higher than those of traditional manufacturing methods. The impossibility of transferring the additional financial burden to consumers, owing to intense global competition, hampers their adoption. Hence, to incentivise immediate investment in these innovations, it is crucial for industry stakeholders to receive unequivocal political assurances that the government will actively support this transformative decarbonisation.

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