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Report on economic assessment of emerging technologies

D7.2

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List of Abbreviations

ADAS	Advanced Driver-Assistance Systems
AFIR	Alternative Fuels Infrastructure
AI	Artificial Intelligence
AV	Autonomous Vehicles
BECCS	Bioenergy with Carbon Capture and Storage
BEV	Battery Electric Vehicle
BF	Blast-Furnace
BOF	Blast-Oxygen-Furnace
C3DP	Cement-based construction 3D printing
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Usage and Storage
CDR	Carbon Dioxide Removal
CEA	Controlled Environment Agriculture
DA	Digital Agriculture
DRI	Direct Reduction of Iron
DT	Digital Twin
EAF	Electric Arc Furnace
EOR	Enhanced Oil Recovery
ETS	Emissions Trading System
EU	European Union
EVs	Electric Vehicles
FCEV	Fuel Cell-based Hybrid Electric Vehicle
GHG	Greenhouse Gas
GDP	Gross Domestic Product
GVA	Gross Value Added
H-DR	Hydrogen direct reduction

HBI	Hot-Briquetted Iron
ICE	Internal Combustion Engine
IEA	International Energy Agency
LC3	Limestone Calcined Clay Cement
LCA	Life Cycle Analysis
LCF	Low Carbon Fuels
LULUCF	Land Use, Land-Use Change and Forestry
MEA	Monoethanolamine
NREL	National Renewable Energy Laboratory
PEV	Plug-in Electric Vehicle
PLA	PolyLactic Acid
PMU	Urban Mobility Plan
PTL	Power-to-Liquid
PV	Photovoltaic
RA	Regenerative Agriculture
SCMs	Supplementary Cementitious Materials
TBF	Traditional Blast Furnace
TEA	Techno-Economic Assessment
TGR	Top Gas Recycling
UAA	Utilised Agricultural Area
V2G	Vehicle-to-Grid
WASP	World’s Advanced Saving Project

Executive Summary

The European Union (EU) has acknowledged the pressing imperative to combat climate change and, to this end, has introduced various policy packages and climate initiatives. These efforts aim to position the EU as a model region in achieving climate neutrality by 2050. The European Green Deal, a comprehensive set of policy measures, solidifies this commitment by charting a path toward a sustainable transition. Central to this vision is the goal of attaining climate neutrality by 2050. Additionally, the EU has intensified its climate actions, setting an interim target of reducing emissions by at least 55% (compared to 1990 levels) by 2030. Recognizing the pivotal role of industries, the European Green Deal emphasizes their contribution to climate neutrality and environmental sustainability. Given that the industrial sector significantly contributes to greenhouse gas emissions and resource utilization, its transformation is essential for achieving the Green Deal's objectives.

This ambitious policy agenda has significant ramifications for local and regional businesses in different sectors across the EU. In this report we focus on three key economic sectors (Manufacturing, Agriculture, and Transportation) with highest contribution to GHG emissions, and provide a repository of 21 state-of-the-art decarbonisation technologies and end-user solutions that can be customized and adopted by regional economic players. Some of these technologies are cross-cutting and can be applied to more than one sector (e.g., carbon removals, switching to low carbon fuels, electrification, and hydrogen). Others have a more specific target sector, and their application and therefore, their decarbonization potential is limited. Nevertheless, the economic assessment of these emerging decarbonization technologies leaves room for the decarbonization of some of the most energy/emission intensive industrial processes in the EU, as well as revealing a gap between the current state of these technologies in terms of costs, potential scale, and required investment to meet the EU climate neutrality by 2050.

In addition to the technoeconomic assessment of decarbonization technologies, this report also provides concrete examples of their applications by reviewing 18 examples in 3 manufacturing subsectors (steel, cement, and chemical) from 6 countries represented by the LOCALISED team (Austria, Germany, Italy, the Netherlands, Poland, and Spain), showcasing the progress among the EU industries towards adopting decarbonization technologies. Together with 4 technology-specific examples and 2 in-depth case studies, these examples provide a benchmark for interested end-user businesses to learn more about the availability and applicability of emerging decarbonization technologies in their sector and among their peers in each country.

Finally, we investigate the labour intensity of the technologies listed in this report by considering the top 3 regions in each country, in terms of the share of employment in the manufacturing sector. Our analysis indicates a high vulnerability of chemical manufacturing in the top industrial regions of Germany and the Netherlands to potential disruptions in labour market due to decarbonization efforts.

1 Introduction

The primary catalyst for global climate change is carbon dioxide emissions. There is a widespread acknowledgment that urgent and substantial reductions in emissions are imperative to avert the severe consequences of climate change. However, the allocation of this responsibility among various regions, countries, and individuals has been a perpetual point of contention in international discussions.

As we step into the 20th century, global emissions were overwhelmingly attributed to Europe and the United States. In 1900, over 90% of emissions emanated from these regions, and even by 1950, they still constituted more than 85% of annual emissions. Nevertheless, a notable transformation has occurred in recent decades. During the second half of the 20th century, there has been a noteworthy surge in emissions from the rest of the world, particularly across Asia, with China standing out prominently. Currently, the United States and Europe jointly contribute to less than one-third of global emissions.

As we can see in Figure 1, global greenhouse gas emissions (GHG) can be categorised based on the economic activities responsible for their generation.

The largest contributor is Electricity and Heat Production, where the combustion of coal, natural gas, and oil for generating electricity and heat stands as the predominant source. Transportation follows, with emissions primarily stemming from fossil fuels used in road, rail, air, and marine transportation. A substantial 95% of the world's transportation energy is derived from petroleum-based fuels, mainly gasoline and diesel. Manufacturing and construction also play a significant role. The category of Other Energy encompasses emissions from the Energy sector not directly linked to electricity or heat production, such as fuel extraction. In the Industry sector, emissions result mainly from on-site combustion of fossil fuels for producing energy and extend to chemical, metallurgical, and mineral transformation processes and waste management activities.

The Agriculture, Forestry, and Other Land Use sector contribute to emissions primarily through agricultural practices (cultivation of crops and livestock) and deforestation. It's worth noting that this estimate excludes the CO2 absorbed by ecosystems, which offsets about 20% of emissions from this sector by sequestering carbon in biomass, dead organic matter, and soils. Understanding these sector-specific contributions is essential for formulating targeted and effective measures to reduce global greenhouse gas emissions.

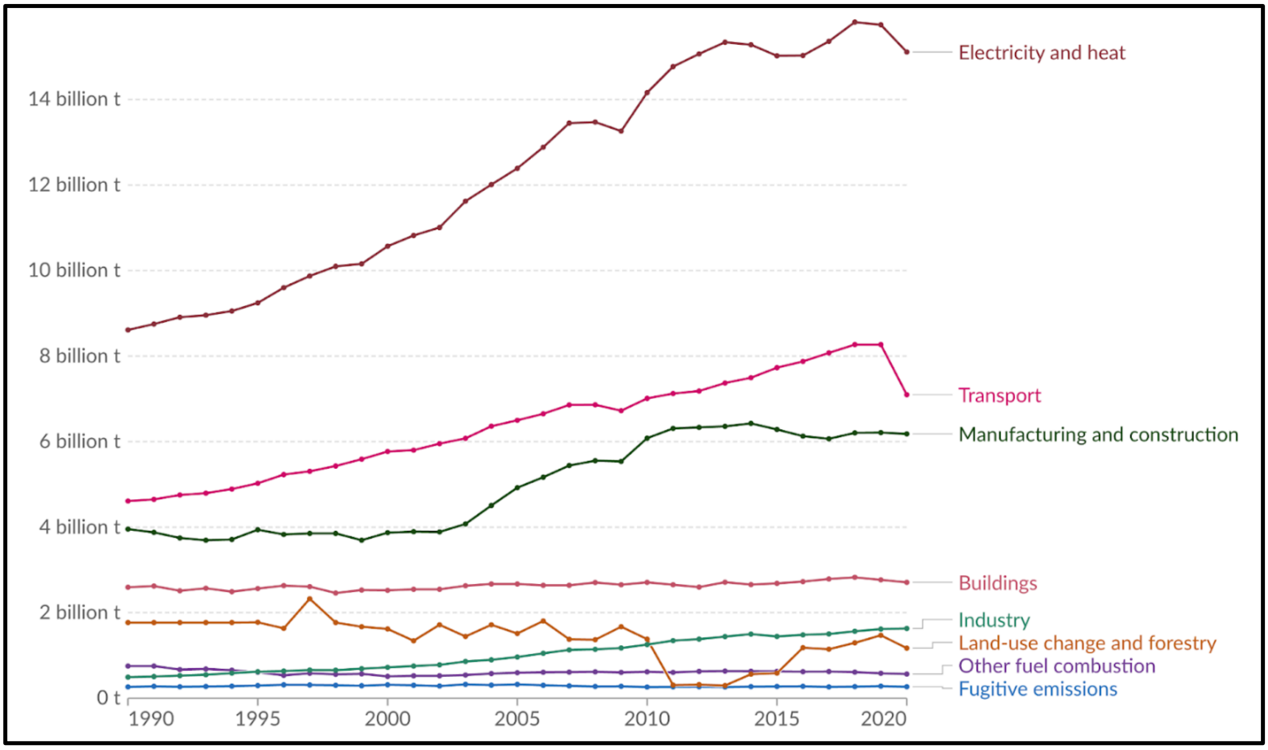

Figure 1: Global CO_2 emissions in different economic sectors[1]

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[1] Climate Watch (2023) – with major processing by Our World in Data. "Buildings" [dataset]. Climate Watch, "Greenhouse gas emissions by sector" [original data].

1.1 Emissions from economic activities in the EU

Greenhouse gas emissions in the EU economy reached 821 million tonnes of CO2-equivalents in the second quarter of 2023, indicating a 5.3% reduction compared to the corresponding period in 2022 when emissions were at 867 million tonnes of CO2-equivalents. During this period, the EU's gross domestic product (GDP) remained relatively stable, exhibiting only a minimal variation of +0.05% in the second quarter of 2023 compared to the same quarter in 2022.

As we can see in Figure 2, during the second quarter of 2023, the primary contributors to greenhouse gas emissions in the economy were the sectors of 'manufacturing' (23.5%), 'households' (17.9%), 'electricity and gas supply' (15.5%), 'agriculture' (14.3%), and 'transportation and storage' (12.8%).

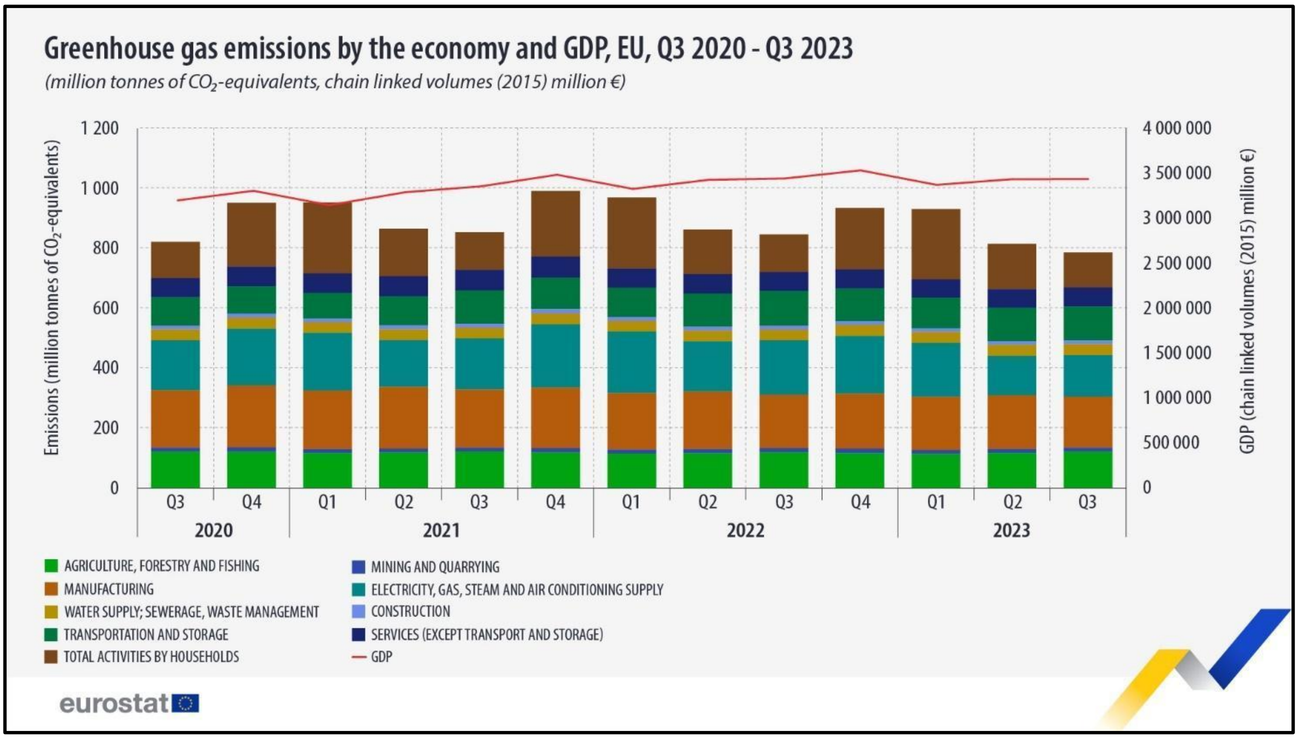

Figure 2: GHG emissions by economic sector and GDP in the EU[2]

Greenhouse gas emissions varied among EU Member States in the second quarter of 2023. In 21 countries, emissions decreased compared to the same period in 2022. Notable increases were observed in Malta (+7.7%), Latvia (+4.5%), Ireland (+3.6%), Lithuania (+3.0%), Cyprus (+1.7%), and Croatia (+1.0%). Among these, four countries experienced a growth in GDP: Malta (+3.9%), Croatia (+2.6%), Cyprus (+2.2%), and Lithuania (+0.7%).

The most significant reductions in greenhouse gas emissions occurred in Bulgaria (-23.7%), Estonia (-23.1%), and the Netherlands (-10.3%). Among the 21 EU Member

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[2] https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240214-1

States with decreased emissions, 10 also witnessed a decline in GDP, including Estonia, Hungary, Luxembourg, Sweden, Austria, Czechia, Poland, Finland, Germany, and the Netherlands. Italy, while maintaining its GDP at the same level as the second quarter of 2022, successfully reduced its greenhouse gas emissions. Additionally, ten EU Member States, including Denmark, France, Belgium, Slovenia, Slovakia, Bulgaria, Portugal, Spain, Romania, and Greece, managed to decrease emissions while concurrently increasing their GDP. Therefore, decarbonization patterns in different countries may have different impacts on the economic growth and productivity of different economic sectors. In other words, decarbonization is not a one-size-fit-all methodology or solution which can simultaneously reduce GHG emissions and stimulate productivity. In what follows, we delve into the specificities of some of the most promising decarbonization technologies to evaluate the conditions under which such technologies and solutions can provide environmental and economic benefits to EU industries.

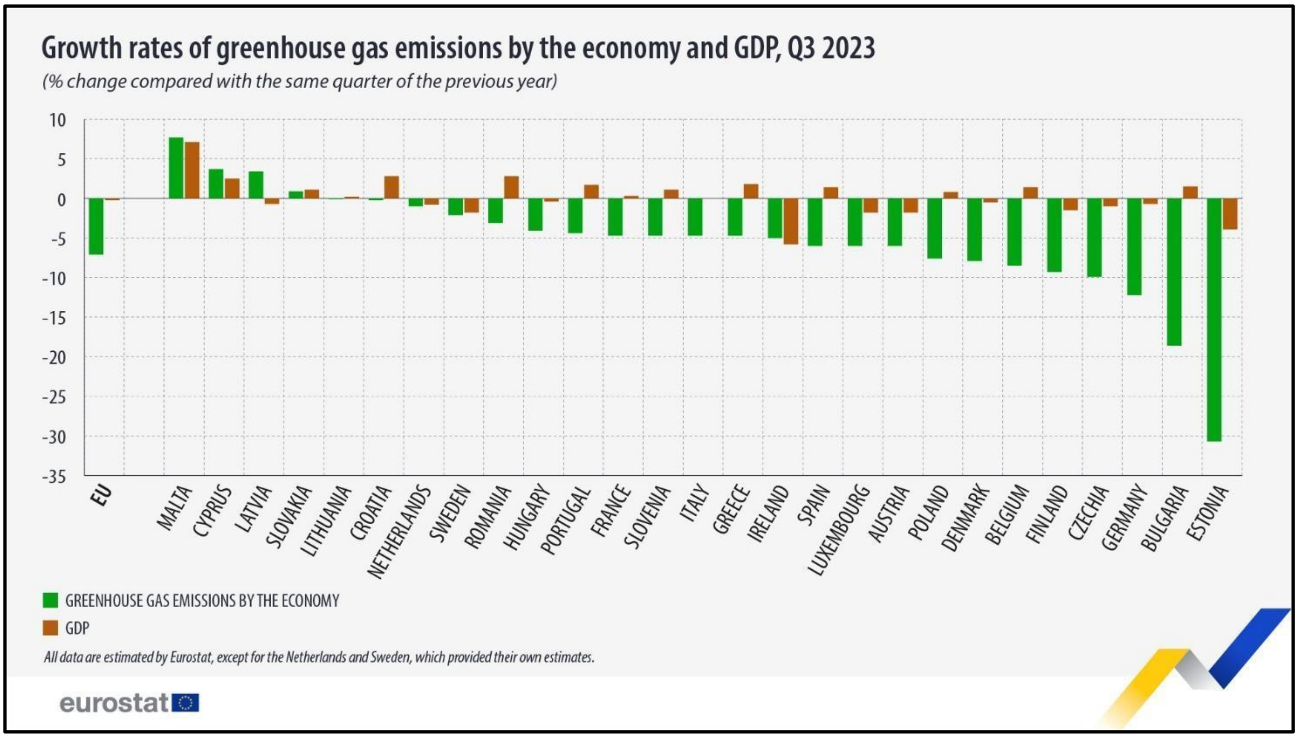

Figure 3: Annual change in GHG emissions and GDP in the EU-27 member countries[3]

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[3] https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240214-1

2 The need for decarbonization in the EU

The EU has recognized the urgent need to address climate change and has put forward several policy packages and climate initiatives aimed at making the EU an exemplary region in terms of achieving climate-neutrality status by 2050. This objective is further enshrined in the **European Green Deal**, a package of policy initiatives for putting the EU on the path toward a green transition, with the ultimate goal of reaching climate neutrality by 2050[4]. Furthermore, the EU has accelerated its climate actions and established an intermediary goal of reducing its emissions by at least 55% (compared to 1990 levels) by 2030[5].

The European Green Deal recognizes the crucial role that industries play in achieving its targets for climate neutrality and environmental sustainability. The industrial sector is a significant source of GHG emissions and resource consumption, making its transformation essential for meeting the goals outlined in the Green Deal. Here are key aspects of the role of industry in achieving the Green Deal targets:

Emissions Reduction: Industries are expected to contribute to reducing their carbon footprint significantly. This involves adopting cleaner technologies, increasing energy efficiency, and transitioning to low-carbon or renewable energy sources.

Innovation and Technology: The Green Deal emphasises the importance of innovation and the development of new technologies to support sustainable practices in industries. This includes investments in research and development for cleaner and more resource-efficient technologies.

Circular Economy: The Green Deal promotes the transition to a circular economy, where products are designed to be more durable, repairable, and recyclable. Industries are encouraged to adopt circular business models that minimise waste generation and promote the reuse and recycling of materials.

Resource Efficiency: Industries are expected to improve overall resource efficiency by reducing raw material consumption and optimising production processes. This involves minimizing waste, water usage, and energy consumption in industrial activities.

Carbon Pricing: The EU has implemented carbon pricing mechanisms, such as the EU Emissions Trading System (ETS), which puts a price on carbon emissions. Industries are incentivized to reduce their emissions as they face financial consequences for exceeding allocated emission allowances.

Regulatory Measures: The Green Deal may involve the introduction and enforcement of regulations and standards to limit emissions and promote sustainable practices in industries. These regulations may set emission reduction targets, mandate the use of cleaner technologies, and establish benchmarks for resource efficiency.

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[4] https://www.consilium.europa.eu/en/policies/green-deal/

[5] https://www.consilium.europa.eu/en/meetings/european-council/2020/12/10-11/

Investment and Financial Support: The Green Deal aims to mobilise financial resources to support the transition of industries toward sustainability. This includes encouraging private and public investments in green technologies, infrastructures, and projects that align with the goals of the Green Deal.

The success of the Green Deal relies on the collaboration between policymakers, businesses, and other stakeholders. Industries are expected to actively participate in the transition to a more sustainable and climate-neutral economy, contributing to the overall success of the Green Deal's objectives.

To enforce the EU's intermediate and long-term objectives, and in line with the European Green Deal, the **European climate law** was adopted in 2021[6] and a new strategy on adaptation to climate change was developed with a vision for making the EU a climate-resilient society by 2050[7]. Finally, EU adopted a wide range of policy reforms under the umbrella of "**Fit for 55**" package to achieve at least 55% reduction in GHG emissions by 2030[8]. This package includes:

- Reforming the EU emissions trading system (EU ETS),
- Establishing social climate funds,
- Implementing the carbon border adjustment mechanism (CBAM),
- Setting member states' emissions reduction targets to 40% for certain sectors
- Setting the target of at least 310 million tonnes of CO2 eq. net removals from land use, land-use change and forestry (LULUCF) by 2030,
- Introducing progressive EU-wide emissions reduction targets for cars and vans for 2030 and beyond, including a 100% reduction target for new cars for 2035,
- Tracking and reducing methane emissions in the energy sector by 30% by 2030
- Adopting ReFuelEU Aviation proposal to reduce the aviation sector's environmental footprint,
- Adopting FuelEU maritime initiative to reduce the GHG intensity of the energy used on-board of ships by up to 80% by 2050,
- Adopting alternative fuels infrastructure (AFIR) regulation to ensure that citizens and businesses have access to a sufficient infrastructure network,
- Increasing the current EU-level target of renewable energy sources in the overall energy mix to at least 40% by 2030,
- Reducing final energy consumption at the EU level by 11.7% in 2030,
- Making buildings in the EU more energy efficient by 2030,
- Shifting from natural gas to renewable and low-carbon gases and boost their uptake in the EU by 2030 and beyond by setting common internal market rules for renewable and natural gases and hydrogen,
- Improving the taxation of energy products and electricity.

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[6] https://www.consilium.europa.eu/en/press/press-releases/2021/06/28/council-adopts-european-climate-law/

[7] https://www.consilium.europa.eu/en/press/press-releases/2021/06/10/council-endorses-new-eu-strategy-on-adaptation-to-climate-change/

[8] https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

2.1 Emerging decarbonization technologies in LOCALISED

The full implementation of EU climate policies will have far-reaching consequences for EU local and regional businesses as they are facing new risks and challenges not only from climate change but also from the shifting international and domestic policy and business landscapes. This report provides an overview of state-of-the-art decarbonisation technologies and end-user solutions that can be customized and adopted by regional economic players.

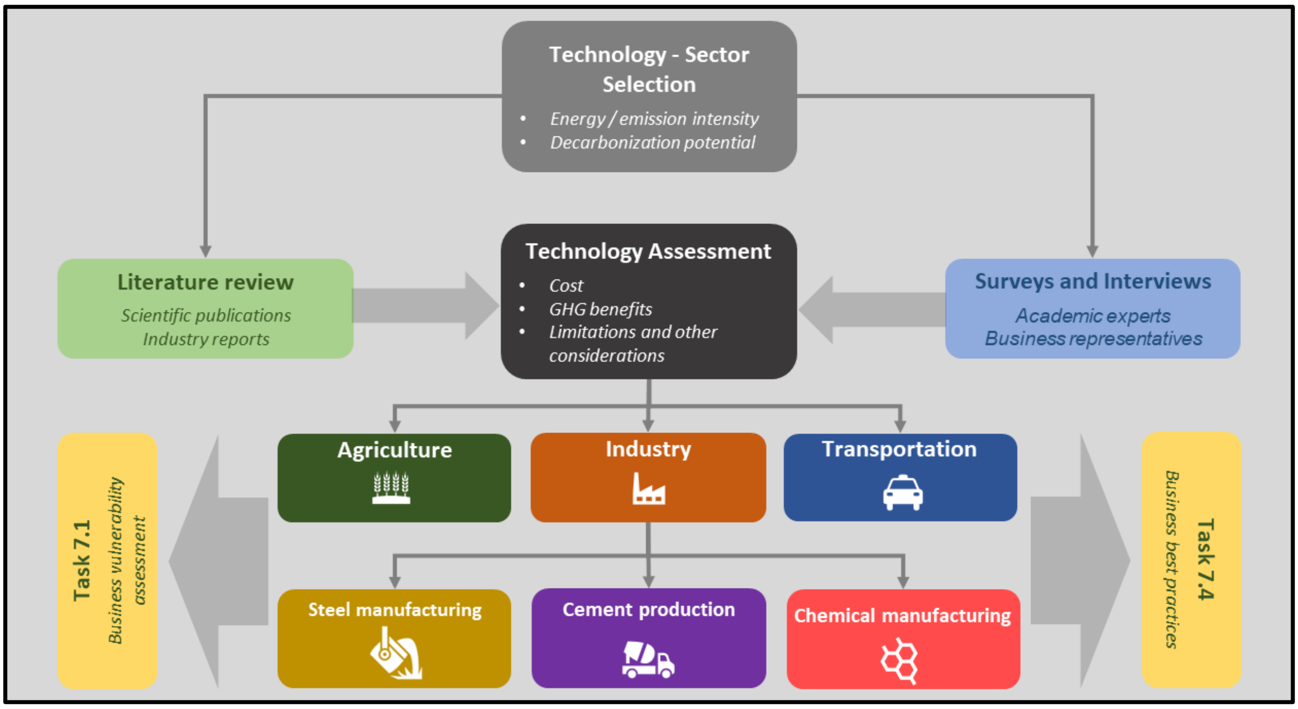

Figure 4: Flow of information in this task and connection with other tasks in LOCALISED

The analyses presented in the following chapters are drawn from a vast, dynamic, and growing literature on decarbonization methods and technologies with an emphasis on their applicability in the EU business context. In doing so, we first identify key economic sectors (manufacturing, agriculture, and transportation) and then focus on the most energy and emission intensive industrial subsectors (steel and iron manufacturing, cement production, and chemical manufacturing). For each sector and subsector, we identify some of the most promising emerging technologies and evaluate their economic viability as well as their decarbonization potential. Since most of these technologies are still in the early stages of development, providing a harmonized quantitative assessment of their performance is subject to many limitations. As a result, we have adopted a more qualitative approach which combines surveys and literature review, with experts interviews to collect their opinion on the prospect of emerging decarbonization technologies. The deliverable also reports examples from various EU businesses in some member states that will provide necessary information for developing business roadmaps in Task 7.4.

2.2 Initial insights from business surveys

As part of Task 7.1 of the LOCALISED project, we have conducted some interviews and surveys of local businesses across different sectors and countries to understand how well EU businesses are prepared for decarbonizing their operations. As part of these surveys, we asked companies to indicate which digital technologies they are using on a regular basis. The initial results from a set of 26 businesses from 5 EU countries (Italy, Spain, Poland, Austria, and Germany) indicates that cloud storage (81%) and management software (69%) are the two main digital technologies adopted by these companies followed by automation technologies (46%).

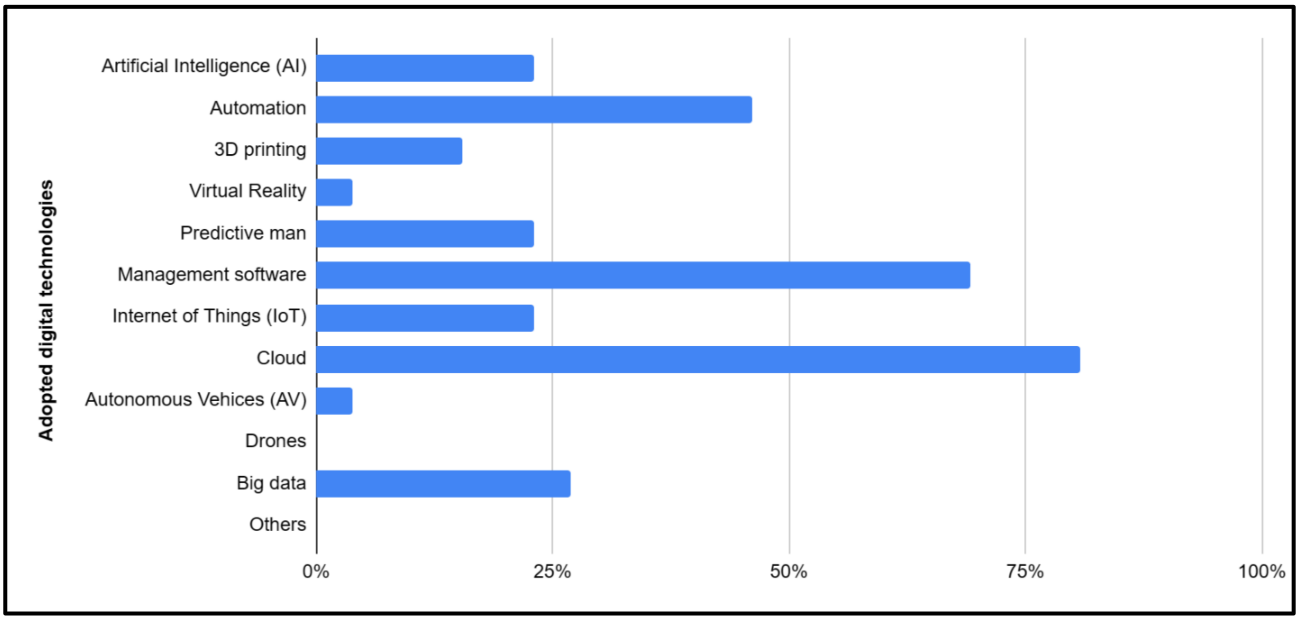

Figure 5: Distribution of digital technologies adoption in surveyed EU businesses

Due to the importance of digital technologies and their decarbonization potential in the industrial processes, we have also devoted two specific case studies of digitalization applications in cement production (i.e., 3D printing) and chemical manufacturing (i.e., digital twins) in section 3.1.4. These case studies show a growing interest in the use of emerging digital technologies for manufacturing.

Similarly, in the transportation sector, the concept of smart cities is gaining momentum in the EU. Smart cities are urban areas that leverage technology and data to enhance various aspects of city life, including transportation, infrastructure, public services, and sustainability. These cities prioritise innovation and efficiency to improve the overall quality of life for residents while addressing environmental challenges and promoting economic development. One key aspect of smart cities is the integration of emerging transportation technologies to create more efficient and equitable mobility systems. These include initiatives such as electric and autonomous vehicles (as discussed in section 3.3.3 of this report), bike-sharing programs, and improved public transportation networks. By ensuring geographic equity in the deployment of these technologies, smart cities aim to provide equal access to transportation options for all residents, regardless of their location or socioeconomic status.

2.3 Insights from expert interviews

We conducted 9 interviews of experts in different fields of engineering, manufacturing, and agriculture. The experts were involved in different sectors representing diverse perspectives from academia, business, and NGOs in Italy, Austria, and France. Here we provide a summary of the technologies discussed during the interviews. More detailed information is provided in Annex 8.4.

2.3.1 Hydrogen direct reduced iron

Another interviewee discussed **hydrogen direct reduced iron** (H-DRI) as a potential solution for reducing carbon emissions in the **steel industry**[9]. They explained that H-DRI offers several advantages over traditional coal-based direct reduction processes. One of the primary advantages is that H-DRI produces no CO2 emissions during the reduction process, with an extremely high decarbonization potential compared to the traditional steel production route (Blast furnace). This expert also highlighted several barriers and challenges associated with the widespread adoption of H-DRI technology: producing hydrogen through processes like electrolysis or steam methane reforming can be expensive and the production capacity is lower compared to the traditional route. Despite the challenges, the interviewee expressed optimism about the prospects of H-DRI, acknowledging it as the needed step in the future to drastically reduce the emission in the steel industry.

2.3.2 3D Printing

One interviewee discussed the environmental impact and potential of **3D printing** technology in **concrete manufacturing**[10]. Initially, they clarified a common misconception about the carbon footprint of 3D printed materials, stating that 3D printed concrete could have a higher carbon footprint than traditional concrete due to the finer aggregate used, necessitating more cement, which increases CO2 emissions per cubic metre. Despite this, they highlighted the intrinsic advantage of 3D printing technology in creating hollow or optimised structural sections that can significantly reduce material usage. The interviewee also pointed out the early stage of 3D printing in the construction industry, emphasising the lack of comprehensive structural and environmental studies and the absence of specific regulations guiding its application. Moreover, they touched on the economic aspect, suggesting that while there are potential cost savings (e.g., less labour and no need for formworks), the technology requires highly specialised knowledge and equipment, which could be a barrier to widespread adoption. Another barrier suggested is the regulatory one, a significant challenge to the adoption of 3D concrete printing. Finally, the expert acknowledged that while there is a potential for 3D printing to contribute to decarbonization and material efficiency, much work remains to be done in optimising mixtures for environmental impact and improving structural applications.

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[9] See section 4.1.1 for more information about this technology.

[10] See section 4.1.2 for more information about this technology.

2.3.3 Digital twins

Three interviewees discussed the importance of **digital twins** in decarbonization[11], indicating the potential of this technology in increasing energy and materials efficiency in **industrial sectors**, its practical application in smart homes and collaborative robotics. The technology's cross-sector applicability also in construction and transportation was emphasized, illustrating its potential to optimize processes, reduce energy consumption, and support circular economy initiatives.

However, the experts acknowledged that this technology presents challenges, including high initial costs, specialised skills required for development, and the need for protecting user accessibility and privacy. Furthermore, they discussed the technology's early adoption stage, noting commercial availability but also pointing to challenges such as interoperability, system complexity, and high costs as barriers to widespread implementation.

They concluded that the potential of the digital twin in decarbonization is significant but uncertain, dependent on the scale of application and the ability to balance the energy consumption of digital systems with efficiency benefits. They emphasised the importance of further research to better understand this trade-off and optimise the use of digital twins towards sustainability goals. Overall, the interviewees were optimistic about the digital twin's potential for contributing to sustainability and efficiency while acknowledging the need for further development and clearer demonstration of its benefits to overcome existing adoption barriers.

2.3.4 New construction materials

One interviewee provided insights into strategies for decarbonizing the **concrete manufacturing** sector. They emphasized the urgent need to reduce CO2 emissions associated with concrete production, particularly from cement manufacturing. Key approaches included the use of alternative cement mixtures with lower CO2 emissions. Additionally, they discussed the potential of innovative additives like strength enhancers to improve concrete resistance and durability while reducing cement content and CO2 emissions, maintaining the same level of material performance. **Geopolymers** were highlighted as a promising alternative to traditional concrete. This new technology allows to obtain more durable products with a lower level of carbon footprint compared to traditional Portland cement. The interviewee also acknowledged challenges such as regulatory constraints in the building sectors and the importance of industry R&D investments.

2.3.5 Inert anodes

One interviewee selected **inert anodes** as a promising technology for decarbonizing the **aluminium sector**, mainly because unlike traditional carbon anodes, inert anodes operate without emitting CO2. Furthermore, inert anodes made from ceramic have a

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[11] See section 4.1.3 for more information about this technology.

longer lifespan and reduced replacement costs than carbon anodes. Additionally, traditional carbon anodes suffer from side reactions that reduce efficiency. Inert anodes minimize these effects, enhancing overall performance. The downside is that inert ceramic anodes are considered a new disruptive technology, and the widespread adoption in existing aluminium smelters requires further research and development.

2.3.6 Alternative agricultural practices

Two interviewees highlighted the benefits of nature-based and alternative solutions for decarbonizing the agricultural sector. Few specific technologies and approaches were mentioned including crop rotation, the use of cover crops, and the use of agricultural waste for energy generation.

Some crops such as legumes can be used as a cover crop to cover the soil between two main harvested crops. This approach significantly reduces the reliance on fertilizers while increasing the food cycle efficiency. As a result, the overall GHG emission of the agricultural sector can be reduced.

Another approach is changing consumers behaviour by encouraging the consumption of products with different quality in terms of colour, size, and shape. This can be done through the relaxation of some aesthetic standards products without compromising the safety protocols.

Finally, the use of precision farming and integrating renewable energy generation with agricultural practices can increase the efficiency and reduce waste in material and energy consumption in this sector[12]. One notable example is the use of agricultural waste in generating biogas for domestic heating. In this approach, a mix of biomass containing at least 70% livestock waste is fed into anaerobic digester and converted into biogas which is used for meeting heating energy demands of residential and local industries. This technology is pretty matured and can substantially reduce GHG emissions. The estimates from France indicate that biogas generates 23-44 gCO2/kWh compared to 227 gCO2/kWh generated from natural gas.

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[12] See section 4.1.4 for more information about this technology.

3 Emerging decarbonisation technologies in key economic sectors

In this section, we build on the insights gained through the surveys and interviews with business owners, academic experts, and practitioners, to analyse some of the emerging decarbonization technologies in 3 key economic sectors of manufacturing, agriculture, and transportation.

3.1 Manufacturing

3.1.1 Key challenges and opportunities

The Net Zero Industry Act is adopted by the EU in line with the European Green Deal to scale up the manufacturing of clean technologies, facilitate the transition of the EU to renewable energies, increase the competitiveness of EU industry, promote quality jobs, and guarantee the transition of the EU to an energy independent entity. This Act supports decarbonization technologies and identifies strategic net-zero technologies with a significant potential for uptake including photovoltaic and solar thermal, electrolysers and fuel cells, onshore and offshore wind, sustainable biogas/biomethane, batteries and storage, carbon capture and storage (CCS), heat pumps and geothermal energy, and grid technologies. Table 1 summarises the decarbonization potential of some of these technologies.

Table 1: Decarbonization potential in the top energy intensive sectors (Verdolini et al. 2023)

	Fuel Switching and electrification	Energy efficiency	Material Efficiency	CCS/CCU	Circular Economy
Steel	High	Medium	High	Medium	High
Cement	Low	Low	High	Medium	Low
Chemical	High	Low	Medium	High	Medium

In this report, we focus on some of these technologies and their applications in 3 specific subsectors[13].

3.1.2 Evaluation of cross-cutting technologies

Carbon Capture and Utilisation/Storage (CCU/S)

Carbon Capture and Storage (CCS) has emerged as a crucial strategy to mitigate GHG, particularly in the industrial sector. As global efforts intensify to combat climate change, reducing CO2 emissions from industrial activities has become a top priority. CCS stands out as a promising technology, offering an additional measure to capture emitted CO2, compress it, transport it, and store it deep underground (Figure 6). Alternatively,

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[13] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan/net-zero-industry-act_en

captured carbon can be used in a variety of commercial purposes from fuel synthesis like methanol, or material synthesis like polymers, to injection fluid for enhanced recovery of materials such as enhanced oil recovery (EOR). While the use of carbon in synthetic fuels or materials does not reduce the amount of carbon in circulation and only eliminate the need for fresh carbon extraction, the use of carbon in enhanced material recovery could partially sequester it permanently into geological formations (Tapia et al. 2018). Traditionally deployed in power plants and energy-intensive industrial processes, CCU/S is gaining traction for addressing hard-to-abate emissions in the industrial sector.

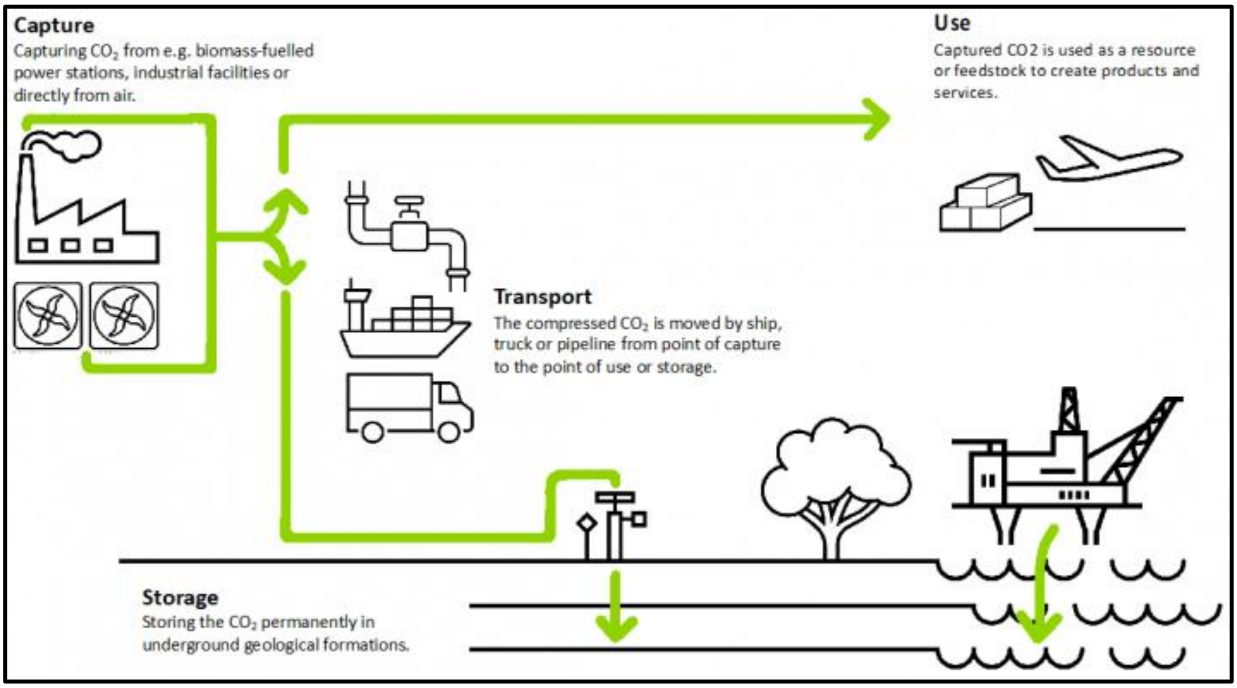

Figure 6: Carbon capture, transport, storage, and use[14]

Potential GHG reduction: Recent studies highlight the pivotal role of CCS in achieving cost-efficient industrial emission reductions. Abating industrial emissions and avoiding a 2-degree Celsius warming by 2100 could be up to 71% cheaper with the integration of CCS, compared to emissions reductions without CCS. CCS projects typically target a 90% efficiency, capturing and storing 90% of the emitted carbon dioxide from industrial processes. However, the potential of CCS to contribute more significantly to climate change mitigation lies in scaling up investments and incentivizing governments and industries to maximise its efficiency. This calls for additional investments to push CCS beyond the conventional 90% capture threshold[15].

Cost estimate: CCS in the industrial sector has garnered attention for being one of the most cost-effective methods to abate emissions. The costs associated with CCS, however, vary significantly depending on the source of CO2. Industrial processes producing "pure" or highly concentrated CO2 streams, such as ethanol production or natural gas processing, have a lower cost range of USD 15-25 per ton of CO2. In

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[14] https://climate.ec.europa.eu/eu-action/carbon-capture-use-and-storage/overview_en

[15] https://climate.mit.edu/ask-mit/how-efficient-carbon-capture-and-storage

contrast, processes with "dilute" gas streams, like cement production and power generation, face a higher cost range of USD 40-120 per ton of CO2. Capturing CO2 directly from the air is the most expensive approach, but it holds unique potential for carbon removal[16].

Hydrogen

Hydrogen has been identified as a key building block in the European energy transition. There are many reasons why hydrogen is a key priority to achieve the European Green Deal and Europe's clean energy transition. Renewable electricity is expected to decarbonise a large share of the EU energy consumption by 2050, but not all of it. Hydrogen has a strong potential to bridge some of this gap, as a vector for renewable energy storage, alongside batteries, and transport, ensuring back up for seasonal variations and connecting production locations to more distant demand centres. In the strategic vision for a climate-neutral EU published in November 2018[17], the share of hydrogen in Europe's energy mix is projected to grow from the current level equal to less than 2% to 13-14% by 2050[18]. Although hydrogen is the Earth's most abundant element, it does not occur naturally in a pure form. Obtaining hydrogen involves separating it from other elements through energy-intensive chemical processes, resulting in varying environmental pollutants. Four main categories of hydrogen exist (Figure 7): grey, blue, turquoise, and green. Grey hydrogen, derived from natural gas and fossil fuels, is the least renewable despite being widely used today. Blue hydrogen, considered a more sustainable alternative, has a lower CO2 impact than grey hydrogen but still emits carbon. Green hydrogen, generated through electrolysis powered by renewable sources, is the most sustainable option, utilising wind, and solar power to separate hydrogen and oxygen molecules, contributing to a cleaner and environmentally friendly hydrogen economy.

Grey hydrogen, produced through conventional methods, boasts a low production cost. However, its carbon intensity remains a critical concern, with emissions ranging from 9 to 12 kgCO2/kgH2. As the global focus on decarbonization intensifies, alternatives with lower emission profiles are gaining prominence.

Blue hydrogen emerges as a promising low-carbon alternative, incorporating carbon capture to mitigate the carbon footprint associated with grey hydrogen production. The additional carbon capture process contributes to an average production cost of USD 1.9/kgH2. Importantly, blue hydrogen achieves a notable reduction in emission intensity, releasing only about 1.8 kgCO2/kgH2, facilitated by a 90% CO2 capture rate. This balance between cost-effectiveness and emission intensity positions blue hydrogen as a transitional solution in the journey towards a sustainable hydrogen economy.

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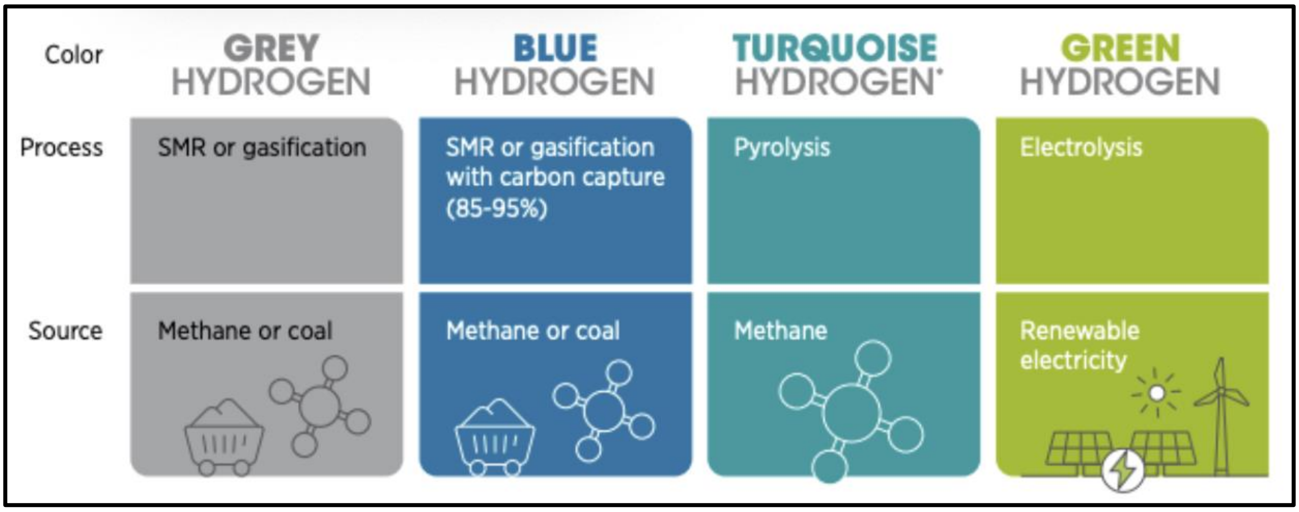
[16] https://www.iea.org/commentaries/is-carbon-capture-too-expensive

[17] European Commission, COM(2018) 773 final

[18] European Commission, COM(2020) 301 final

Turquoise hydrogen represents a hybrid between blue and green hydrogen, utilising 'methane pyrolysis.' Unlike traditional methods, it generates heat with electricity instead of fossil fuel combustion. This process produces hydrogen and solid carbon without emitting CO2, eliminating the need for carbon capture. The solid carbon byproduct has versatile applications, such as soil improvement or manufacturing goods. When powered by renewable electricity or biomethane, the turquoise hydrogen process becomes zero-carbon or even carbon negative, showcasing its potential as an environmentally friendly hydrogen production method.

Green hydrogen, produced through electrolysis powered by renewable energy sources, holds immense potential for zero-emission hydrogen production. However, its current production cost remains higher than that of grey and blue hydrogen, making it less economically competitive at present. The environmental benefits, characterised by zero CO2 emissions during production, classify green hydrogen as a key player in the long-term strategy for a carbon-neutral hydrogen sector.



Color	GREY HYDROGEN	BLUE HYDROGEN	TURQUOISE HYDROGEN*	GREEN HYDROGEN
Process	SMR or gasification	SMR or gasification with carbon capture (85-95%)	Pyrolysis	Electrolysis
Source	Methane or coal	Methane or coal	Methane	Renewable electricity

Figure 7: Hydrogen production and its source[19]

Hydrogen in steel manufacturing: There are two prominent methods of integrating hydrogen into steel production, namely hydrogen as an auxiliary reducing agent in the blast-furnace (BF) or blast-oxygen-furnace (BOF) route (H2-BF), and the use of hydrogen as the sole reducing agent in the Direct Reduction of Iron (DRI) process (H2-DRI). As global steel manufacturing seeks sustainable alternatives to reduce carbon emissions, the utilisation of hydrogen presents a promising avenue for achieving significant decarbonization in the steel production process. The BF-BOF route, responsible for 60% of steel production in Europe, has been a major source of carbon emissions. The introduction of Hydrogen as an auxiliary reducing agent in the BF-BOF route (H2-BF) offers a transitional solution to mitigate emissions. By reducing the dependence on coal in the coke plant and blast furnace, H2-BF minimises CO2 emissions and produces water instead. This method is seen as a stepping stone toward H2-DRI, where hydrogen acts as the sole reducing agent. Technical challenges currently limit the feasibility of using hydrogen exclusively in a blast furnace, prompting the industry

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[19] https://www.weforum.org/agenda/2021/07/clean-energy-green-hydrogen/

to view H2-BF as a transition phase. Despite this, several European steel producers are actively planning and implementing H2-BF projects to achieve significant emission reductions in the near term. H2-DRI is envisioned as the long-term solution to completely decarbonize steel production.

Hydrogen Production from Electrolysis: The source of hydrogen plays a crucial role in determining its environmental impact. Electrolysis powered by renewable energy emerges as the preferred method, offering substantial emission cuts (approximately 21%), when integrated into the BF-BOF route. However, challenges related to the availability, cost, and quantity of green hydrogen remain, prompting companies to opt for grey hydrogen in the interim.

Potential GHG reduction: Hydrogen has the lowest carbon footprint possible among all fuels. The combustion of H2 emits no CO2, and therefore, the only GHG emissions related to H2 come from its production process and not from its utilisation.

Cost estimate: grey hydrogen is cheap (USD 1.3/kgH2 production cost). Blue hydrogen involves using carbon capture to trap the CO2 emissions of grey hydrogen. The additional carbon capture process raises the cost of blue hydrogen to an average of USD 1.9/kgH2 but results in a low-emission intensity of roughly 1.8 kgCO2/kgH2 with 90% CO2 capture (Woodall et al. 2022).

Fuel switching

As the term suggests, fuel switching involves the replacement of an inefficient fuel source with a cleaner, more efficient, or cost-effective alternative. This process extends to various contexts, from replacing gas furnaces with electric air-source heat pumps to transitioning from oil-based heating to geothermal energy. In the realm of transportation, it encompasses the shift from traditional gasoline-powered vehicles to electric vehicles.

One facet of fuel switching is **electrification**, wherein technologies relying on coal, oil, and natural gas are substituted with those powered by electricity. This approach gains prominence in strategies for building decarbonization, reflecting a broader trend toward cleaner energy sources. Due to its importance, we will discuss this decarbonization solution separately in the next section.

In the manufacturing sector, fuel switching takes on a pivotal role in decarbonization efforts. **Biomass**, involving the combustion of organic materials, emerges as a renewable alternative for supplying essential process heat, reducing reliance on fossil fuels. Simultaneously, the combustion of hydrogen, sourced from clean production methods, serves to achieve the high temperatures crucial for processes like cement manufacturing.

The benefits of fuel switching, whether towards biofuels or electrification, are significant, potentially resulting in a commendable 30% reduction in greenhouse gas emissions. Electrification, in particular, holds advantages by ensuring a pure CO2 stream, streamlining the carbon capture process for enhanced efficiency. Beyond environmental gains, this contributes to economic viability, as the improved carbon capture process can substantially lower associated costs, fostering a more feasible transition to a low-carbon manufacturing sector.

Amidst rising energy prices and an increasing emphasis on low-carbon fuels, fuel switching becomes an attractive option for homeowners. The transition not only holds the potential for lower operational and maintenance costs but also aligns with efforts to reduce carbon emissions. Additionally, fuel switching offers benefits such as increased energy efficiency, improved indoor air quality, and enhanced safety. Utility companies can play a role by incentivizing fuel switching through rebates and incentives, further encouraging a shift toward cleaner energy sources in residential and commercial settings.

Potential GHG reduction: Fuel switching from fossil fuels to biofuels or via electrification, can potentially cut the GHG emissions by approximately 30%. Considering that fuel switching to biofuels still generates biogenic CO2 and other emissions, electrification offers more advantages since the CO2 stream will be pure, which eases CO2 capture. This can significantly lower the cost associated with CCS (Nurdiawati and Urban 2021).

Cost estimate: The cost estimate of fuel switching depends on two main factors: the original fossil-fuel that this method is aimed at replacing, and the destination fuel (such as hydrogen or electricity). Therefore, providing a cost range for this method without a full technical assessment is not very informative. In the next sections of this report, we will try to provide specific estimates for certain applications of this method.

Electrification

Decarbonization through electrification in the manufacturing sector is a multifaceted strategy encompassing three distinct tiers of low-carbon electricity use. First tier targets applications already electrified but reliant on fossil-based electricity. Second tier focuses on electrifying process units utilising low-temperature heat, such as boilers producing steam and units employing steam, like compressors and distillation columns. The third tier extends electrification to units requiring high-temperature heat or high capacities, including steam crackers, gasifiers, and methanol synthesisers. Leveraging low-carbon electricity, particularly from renewable sources like wind or solar, presents a cost-effective approach for industrial emissions abatement. Despite the declining prices of renewable energy, challenges persist, including the need for a reliable supply of low-carbon electricity.

Potential GHG reduction: Electrification holds significant potential for reducing CO2 emissions in industry, a crucial step towards achieving the EU's 2050 climate neutrality target. A comprehensive analysis of 11 industrial sectors, which account for 92% of

Europe's industry CO2 emissions, has revealed that 78% of energy demand (Figure 8) can be electrified using established technologies, and nearly 99% can be electrified with technologies currently under development (Madeddu et al. 2020). This deep electrification could lead to a substantial reduction in CO2 emissions, even based on the current carbon intensity of electricity, potentially cutting emissions by 78%. As the power sector decarbonizes further, with an anticipated decrease in carbon intensity from 300 gCO2/kWh in 2015 to 108 gCO2/kWh in 2030, electrification could provide a prominent solution for the decarbonization of all industrial processes, leaving only residual process emissions. However, the extent of direct electrification deployment in industry hinges on factors such as the relative cost of electric technologies compared to other low-carbon alternatives.

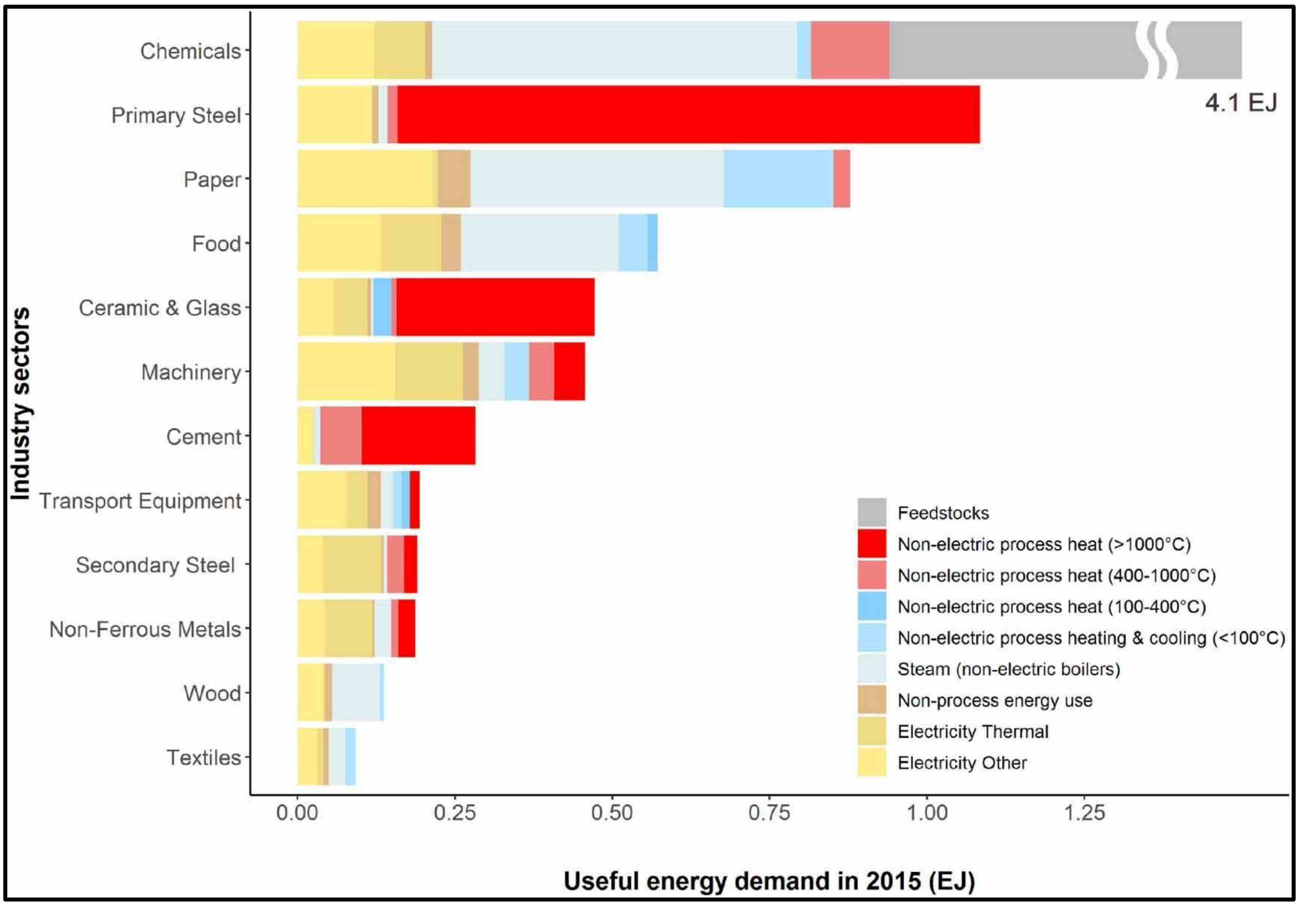

Figure 8: Energy demand in the EU industries in 2015 (Madeddu et al. 2020).

Cost estimate: Electrode boilers, a prominent technology in the second tier, offer a commercially available solution for generating steam using electricity, demonstrating affordability with a price of approximately EUR 170 per kW and a 15-year service life. This approach mirrors the broader trend observed in other sectors, such as transportation and buildings, where the transition from fossil fuels to electricity not only reduces carbon emissions but also generates significant air quality improvements, particularly in indoor environments.

Nuclear heat

Nuclear heat emerges as a pivotal player in the decarbonization efforts within the manufacturing sector. Traditionally, almost all nuclear energy has been harnessed by converting nuclear heat into steam to drive turbines, a process observed in generation II and III nuclear reactors. Remarkably, steam alone contributes to a substantial 30% of the total heat generation in the United States. The evolution of generation IV nuclear reactors presents a significant advancement, offering higher available temperatures and a diverse array of heat mediums, thus expanding the possibilities for industrial heat applications. As these reactors continue to develop, the potential for integrating nuclear heat into manufacturing processes becomes increasingly promising.

Potential GHG reduction: Every year, nuclear-generated electricity saves our atmosphere from more than 470 million metric tons of carbon dioxide emissions that would otherwise come from fossil fuels[20].

Cost estimate: The generation of electricity through nuclear power plants in the United States cost USD 29.13 per megawatt-hour in 2021. Production costs were highest in 2012, when they came to over 47.6 U.S. dollars in 2021 prices but have decreased ever since[21].

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[20] https://www.nei.org/advantages/climate

[21] https://www.statista.com/statistics/184754/cost-of-nuclear-electricity-production-in-the-us-since-2000/

3.1.3 Evaluation of Specific technologies

3.1.3.1 Steel manufacturing

Steel can be obtained via two main processes: primary production and secondary production. In primary production, steel is obtained from iron ores, with the most widely used method being the Blast Furnace to Blast Oxygen Furnace (BF-BOF). In secondary production, steel is derived from recycled steel scrap using an Electric Arc Furnace (EAF). Around 74% of the world's steel was obtained using the BF-BOF method in 2019, while 26% was produced through the EAF. Another less common method is the Direct Reduction (DR) of iron, accounting for about 5.6% of the steel produced via the EAF (Verdolini et al. 2023).

Multiple strategies have been identified for reducing GHG emissions in the steel industry, including enhancing energy efficiency in BF-BOF systems by up to 15%, and encouraging recycling to minimise reliance on primary production (Verdolini et al. 2023). Additionally, transitioning to carbon-neutral energy sources, incorporating carbon capture and storage (CCS) technologies, and exploring fuel switching could potentially reduce emissions by up to 80% in traditional BF-BOF operations. Lastly, enhancing material efficiency and moving towards circularity could lower steel demand, with the International Energy Agency (IEA) suggesting a potential 40% reduction by 2060. Hydrogen Direct Reduction (H-DR) is a steel production process utilising hydrogen as a reduction agent instead of coal or natural gas to reduce iron ore. A reduction agent facilitates the removal of oxygen from the ore. The output of this process is sponge iron, subsequently used as an input in EAF to produce steel. The H-DR technique could theoretically achieve zero emissions if the hydrogen used in the reduction process and the electricity used for the EAF are generated through renewable sources (Vogl, Åhman, and Nilsson 2018). Achieving zero emissions in this process requires carbon capture and storage technologies[22].

Top-gas recycling blast furnace

The blast furnace (BF) plays a pivotal role in the steel production process, being fed with a combination of iron ore, limestone, and coke to generate liquid iron, subsequently converted into steel in a basic oxygen furnace (BOF). In the BF process which consumes about 75% of the total energy, coke and iron ore, known as the burden, enter from the top of the BF while hot air is injected from the bottom. Modern blast furnaces, boasting dimensions as large as 15 m in diameter and 35 m in height, can produce up to 10,000 tonnes of hot metal daily. The furnace operates with a temperature gradient ranging from 200 °C at the top to temperatures exceeding 1600 °C at the bottom. The process involves the addition of iron ore and coke in layers, with preheated air or oxygen-enriched air injected at the bottom. The resulting hot blast reacts with coke layers, producing carbon monoxide (CO) that rises through the furnace, reducing iron ore to

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[22] https://bellona.org/publication/electrolysis-hydrogen-production-in-europe

metallic iron and transferring heat upwards. Once metallic iron forms, it collects at the furnace bottom for extraction. Impure iron ore is treated with limestone and additives to separate impurities, resulting in the production of molten slag, which is tapped from the furnace. The blast gas, along with carbon monoxide and carbon dioxide, rises to the top as top gas, leaving the furnace at 200–300 °C. This top gas's recovered heat, combined with additional combustion heat, is used to preheat the blast to over 1100 °C. The intricacies of the blast furnace process highlight its significance in steel production and the potential for innovative approaches to reduce emissions and enhance efficiency (Kildahl et al. 2023).

To increase the efficiency of this process and reduce coke consumption, pure oxygen, instead of hot blast, can be injected into the BOF (Takahashi et al. 2015). Furthermore, CO2 can be extracted from the exhausted gas to be recycled into the blast furnace after being heated as shown in Figure 9. This method is called Top-gas recycling blast oxygen furnace (TGR-BOF) and compared to traditional BF, has a theoretical potential of reducing CO2 emissions and carbon consumption by 76% and 24%, respectively (Zhou et al. 2020). Due to higher concentration of CO2 in the top gas of TGR-OBF, the removed CO2 through this process can also be used in the production of methanol.

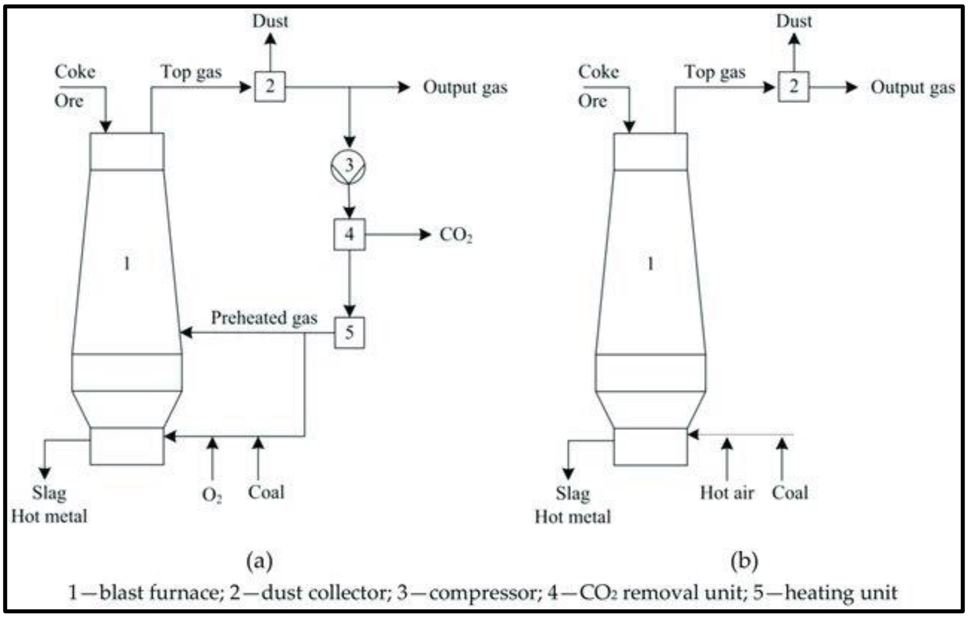

Figure 9: Schematic diagrams of (a) oxygen blast furnace with top gas recycling (TGR-BOF) and (b) traditional blast furnace (TBF) (Zhou et al. 2020).

Potential GHG reduction: A computational fluid dynamics model for analysing the performance of different steel making technologies show that when evaluating the performance of a conventional blast furnace against TGR-BOF system, the output of the OBF improved by 5.3% to 35.3%, and energy savings ranged from 27.3% to 35.9%, depending on the chosen energy consumption criteria (L. Liu et al. 2018).

Cost estimate: There are two specific examples of TGR in Europe: Carbon2Chem by ThyssenKrupp[23] and Steelanol by ArcelorMittal.[24]

- **Carbon2Chem:** This project focuses on developing a chemical conversion process at a quasi-industrial scale. Its goal is to transform portions of the top gas from coke ovens, blast furnaces (BF), and basic oxygen furnaces (BOF) into ammonia and methanol. An industrial-scale plant is planned for establishment by 2025. Although the investment requirement estimates are higher, the German federal government has committed to provide this project with external funding of over EUR 60 million.
- **Steelanol:** This initiative aims to treat approximately 15% of available top gases from a blast furnace (BF) and convert them biologically into bioethanol. The corresponding Horizon2020 project has a budget of EUR 87 million, and the total investment amounts to EUR 120 million.

These examples highlight massive investment needs in the range of EUR 100-150 million for enhancing the technological maturity of both chemical and biological routes (De Santis et al. 2021).

Smelting reduction

Smelting reduction processes represent the most recent advancement in pig iron production. This method combines coal gasification with the melt reduction of iron ore. The energy intensity of smelting reduction is lower than that of a blast furnace because it eliminates the need for coke production and reduces the requirement for ore preparation (Figure 10). Metals like nickel, cobalt, copper, and aluminium, which are essential for the energy transition and decarbonization efforts, are produced through smelting operations worldwide. To align with the growing need for metals in association with minimal carbon footprints, a shift towards sustainable smelting practices is taking place. Smelting is inherently energy-intensive, historically relying on grids with mixed renewable and non-renewable sources or onsite generation from hydrocarbons or coal. Achieving sustainable smelting necessitates a transition to a 100% renewable energy supply through grids, clean onsite generation, or engagement with offsite renewables. Smelters are increasingly committing to powering their operations with dedicated solar and wind power, aligning with the broader industrial trend. While the use of renewable energy mitigates carbon emissions from power consumption, the smelting process itself, involving the decomposition of metal ore through carbon-based reductants, inherently produces CO2. Carbon capture emerges as a solution, with captured CO2 potentially stored in various formations or even reintegrated into the smelting process as part of synthetic gas. Since these approaches are in their early stages, ongoing advancements are expected, offering promising avenues for more sustainable and low-carbon smelting practices in the future.

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[23] https://www.thyssenkrupp.com/en/company/innovation

[24] http://www.steelanol.eu/en

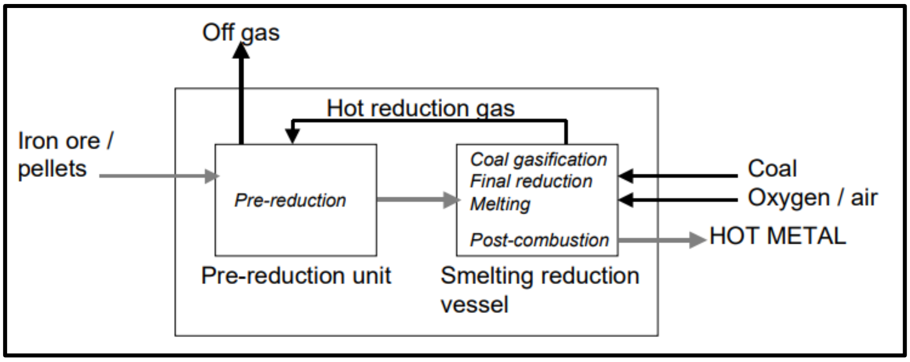

Figure 10: Schematic layout of smelting reduction technology (Lutz et al. 2007).

Although Smelting Reduction can help reduce steel manufacturing costs by replacing cheaper non-coking coal with coking coal, it needs a higher energy input which limits the overall CO2 reduction potential. This calls for the integration of carbon capture and storage technologies (CCS) with smelting reduction methods, which in practice (such as the HIsarna program[25]), can lead to a reduction level of about 20% of CO2 per ton of steel produced (Cavaliere 2019a).

Direct reduction

Direct Reduced Iron (DRI), used especially in steel production, is obtained through the solid-state reduction of iron ore using carbon monoxide and hydrogen derived from natural gas or coal. Typically integrated into steel mini-mills, DRI plants are commonly located near electric arc furnace (EAF) steel facilities where high-quality steel grade is produced. DRI can act as a substitute for premium scrap and pig iron to increase the quality of the overall scrap mix (Mohsenzadeh et al. 2019).

DRI can be hot or cold charged to the EAF, with some companies transporting it from captive plants to remote steel mills, and a portion being sold to third parties. In India, small rotary kiln furnaces produce DRI, known as sponge iron, utilising coal as an energy and reductant source. Despite being a valuable material, DRI poses challenges due to its high reactivity and susceptibility to re-oxidation. This exothermic reaction may lead to self-heating and fire risks during handling, transport, and storage. To mitigate these risks, the International Maritime Solid Bulk Cargoes Code classifies DRI as Group B (chemical hazard) and class MHB (material hazardous only in bulk). Consequently, shipping DRI requires adherence to safety protocols, including transportation under an inert atmosphere, typically nitrogen.

Figure 11 shows how a DRI plant works:

- DR pellets, serving as the raw material, are introduced into the reactor.
- Hydrogen, acting as the reducing gas, undergoes circulation within a closed-loop system before being recycled.

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[25] https://www.tatasteeleurope.com/sites/default/files/tata-steel-europe-factsheet-hisarna.pdf

- The hot-reducing gas flows through the iron ore, following the counterflow principle from bottom to top. This process reduces the oxygen content within the iron ore, resulting in the production of DRI.
- The obtained DRI is then formed into Hot Briquetted Iron (HBI) through pressing.

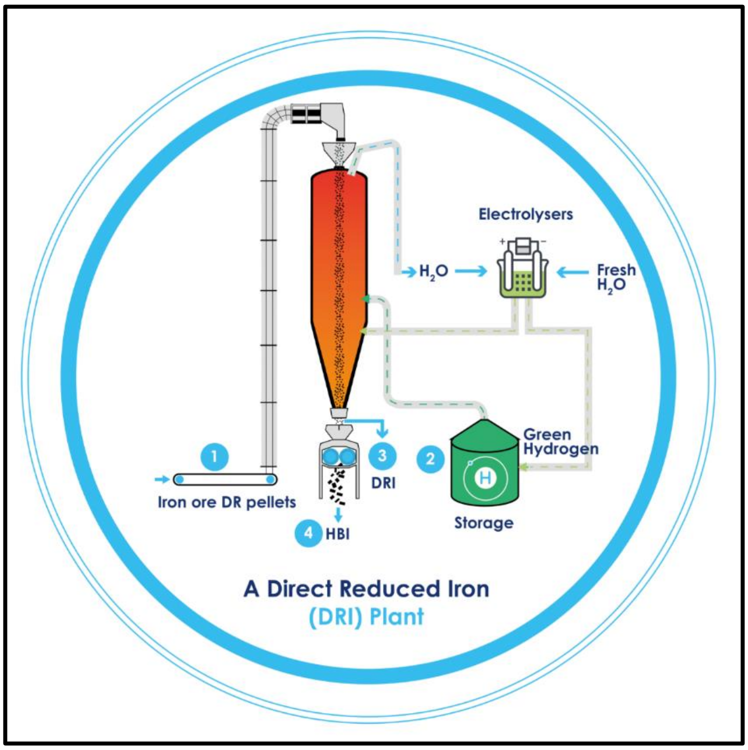

Figure 11: Schematic layout of direct reduction iron technology[26]*.*

Potential GHG reduction: DRI energy consumption is about 10.4 GJ/t-DRI which is equivalent to 300 m3 of natural gas per ton of reduced iron. The CO2 emissions are about 0.77–0.92 tonne of CO2 per ton of steel (Cavaliere 2019b). If the DRI production utilises pure hydrogen as a reducing gas, generated through renewable means like water electrolysis, a significant reduction in CO2 emissions might be possible. Under optimal operating conditions, utilising 400 kg/tHM of DRI (tHM = ton of produced hot metal), the blast furnace's CO2 emissions can decrease by up to 26.7% compared to conventional operations employing pulverised coal injection rates of 120 kg/tHM (Yilmaz and Turek 2017).

Cost estimate: Since DRI uses natural gas, its cost highly depends on the availability and the price of natural gas. As a result, most DRI facilities are located near natural gas resources. Currently, capital expenditures for commercial plants are between USD 200 and 350 per ton and the production costs (depending on iron ores and gas price variations) are between USD 200 and 350 per ton (Cavaliere 2019b). With more sustainable energy options, such as renewable H2 used in integrated DRI steel mills for both heating and reducing iron ore, the emissions decreased by 85%, but this would require a procurement cost of USD 1.63 per kg of H2 or less. When using H2 only for iron ore reduction, economic viability is reached at a procurement cost of USD 1.70 per

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[26] https://libertysteelgroup.com/delivering_cn30/a-direct-reduced-iron-dri-plant/

kg of H2, while achieving a CO2 emission reduction of 76% at the plant site (Rosner et al. 2023).

Electric arc furnace

The electric arc furnace (EAF) is a pivotal tool in the metallurgical industry, employing an electric arc and chemical energy from oxygen and fuel to heat materials for various processes. Unlike induction furnaces, where the charge is heated by eddy currents, EAFs directly expose the charged material to the electric arc, with current passing through the material via furnace electrodes (Figure 12). Technological advancements have played a crucial role in enhancing the efficiency and productivity of EAFs. Increased power usage, made possible through these developments, has significantly boosted melting unit productivity. The contemporary electric arc furnace stands out as a versatile piece of equipment, capable of melting diverse charge mixes, ranging from 100% scrap to 100% direct reduced iron (DRI)/hot-briquetted iron (HBI), and everything in between, including the utilisation of hot metal.

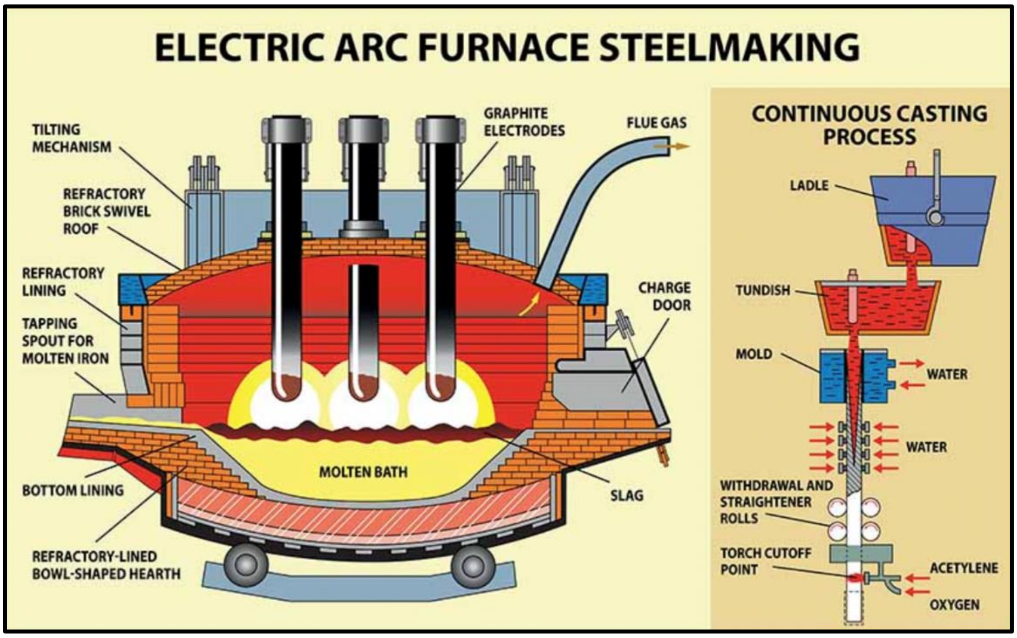

Figure 12: Electric arc furnace steelmaking[27].

Potential GHG reduction: Average emissions for every ton of steel produced by EAF in the U.S. is about 0.37 t CO2 while it is around 1.67 t CO2 for a ton of steel produced by BOF technology. In other words, EAF has a carbon intensity of about 75 percent lower than traditional steel produced by BOF[28].

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[27] https://www.steelsupplylp.com/blog/electric-arc-furnace-vs-blast-furnace

[28] https://steelnet.org/steelmaking-emissions-report-2022/

Cost estimate: There are several components which contribute to the total cost of steel production with EAF technology: raw material and steel scrap, energy, labour, and electrodes. The production cost of one tonne of steel with EAF is around EUR 600-700 while the BF costs are usually EUR 60-100 higher than that.

3.1.3.2 Cement production

The European cement industry plays a substantial role in the EU economy. In 2019, it directly employed over 36,000 individuals, contributing to around EUR 4 billion in terms of direct Gross Value Added (GVA) in EU27. This presence persisted in 2020 with about 35,176 people in EU28. Additionally, when considering the sector's indirect influence through its supply chains, it is linked to approximately 13 million jobs and 10% of the EU's Gross Domestic Product. The industry's impact spreads across multiple Member States through production sites and related value chains (Marmier 2023).

Cement and lime production significantly contributes to the EU economy. Cement is vital for construction and civil engineering, while lime is indispensable for steel, construction materials, paints, plastics, and rubber. Environmental concerns drive innovation, including waste utilisation as alternative raw materials and fuels. The production process is energy-intensive, with energy costs comprising up to 40% of total cement production costs and up to 50% for lime. The industry's emphasis on sustainability is evident due to its environmental impact and role in critical economic sectors[29].

The cement industry holds a significant position as a major contributor to CO2 emissions. On a global scale, it accounted for roughly 2.5 billion tons of CO2 emissions in 2020, amounting to 7.1% of the world's total emissions that year. In the EU27, cement production led to around 110 million tons of CO2 emissions, comprising 8.2% of the emissions reported through the Emissions Trading System (ETS) and approximately 4% of the EU27's total CO2 emissions. In conjunction with the iron and steel sector, the cement industry stands out for having the highest overall CO2 emissions among energy-intensive industries. Cement production is responsible for around 8% of the total global emissions (Gangotra, Del Gado, and Lewis 2023). During the process of cement production, clinker is produced by heating materials, mainly limestone and clay, in a cement kiln. The most used type of cement is Portland cement, which is created by grinding raw materials like limestone and clay/shale into a powder. This powder is then heated in a kiln to temperatures ranging from 1450°C to 1500°C (Habert 2013). As a result of this process, the clinker is formed, obtaining the Portland cement grounding the clinker with gypsum. This heating process triggers a chemical reaction that transforms the materials into compounds like tricalcium silicate, dicalcium silicate, tricalcium aluminate and tetracalcium aluminoferrite. These compounds are responsible for providing Portland cement with its properties. More than 50% of the emissions related to the production process are caused by the calcination chemical processes, and 40% of emissions are related to the energy required for the calcination process itself (Gangotra, Del Gado, and Lewis 2023).

A primary approach to decarbonize the cement industry is enhancing material efficiency by improving concrete mixtures, which can reduce cement usage by 20-30%. Another

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[29] https://single-market-economy.ec.europa.eu/sectors/raw-materials/related-industries/non-metallic-products-and-industries/cement-and-lime_en

potential strategy for emissions reduction is fuel switching and electrification, especially in the production phase where bioenergy, hydrogen, or electricity could replace traditional fuels. Carbon capture and storage (CCS) technology also emerges as a critical solution for capturing emissions from the cement industry, targeting both process and energy-related CO2 emissions. Furthermore, transitioning towards alternative materials and production processes represents a long-term strategy for deep decarbonization. Utilising supplementary cementitious materials (SCMs) from industrial or agricultural waste to replace clinker and exploring innovative cements like Limestone Calcined Clay Cement (LC3) and other low-carbon binders, could significantly cut CO2 emissions.

Monoethanolamine (MEA) absorption

In the cement manufacturing process, the extraction of carbon dioxide (CO2) is a critical consideration for mitigating environmental impact. The process involves three main stages: mixing and crushing raw materials (limestone and clay) to form raw meal, pyro-processing through a series of devices to produce clinker, and finally, crushing and grinding the clinker into commercial cement by mixing it with additives. To enhance the reduction of CO2 emissions and lower costs, a proposed manufacturing process incorporates high-temperature energy storage materials such as Barium carbonate/oxide (BaCO3/BaO), Strontium carbonate/oxide (SrCO3/SrO), and Silicon (Si). In particular, thermochemical energy storage with BaCO3/BaO at 1300 °C has appeared to be significantly promising. In the realm of chemical absorption for CO2 removal from gas streams, monoethanolamine (MEA) stands out as a well-developed and widely used solvent, particularly when treating sour natural gas. The utilisation of MEA in the cement manufacturing process exemplifies a practical approach towards efficient CO2 capture.

Potential GHG reduction: The proposed manufacturing process with a few high-temperature energy storage materials (BaCO3/BaO, SrCO3/SrO, Si, etc.) offers a higher CO2 emission reduction as well as lower cost than alternative carbon capture routes, such as oxyfuel.

Cost estimate: The cost of CO2 avoided as low as USD 39.27 per tonne can be achieved by thermochemical energy storage with BaCO3/BaO at 1300 °C, which is superior to all alternative technologies evaluated in recent studies (X. Liu, Li, and Yang 2022).

Clinker substitution

Clinker substitution has emerged as a strategic approach within the cement and concrete industry to achieve CO2 reduction goals while prioritising energy and natural resource conservation. Utilising low-clinker cements offers a range of environmental benefits, including energy savings, reduced pollutants, lower consumption of raw materials, and the incorporation of waste products that would otherwise harm the environment.

Potential GHG reduction: The Swedish cement industry uses an energy efficient dry kiln process and estimates that only 2–3% of emission reductions can be achieved through energy efficiency improvements. The Swedish cement has an average clinker content of 83%. By replacing parts of the clinker with other materials, such as fly ash and slag, the clinker content can be lowered, reducing CO2 emissions from cement production. A blast furnace slag, a byproduct of steel production, is one of the most promising clinker substitutes that could potentially reduce emissions by around 15–60% (X. Liu, Li, and Yang 2022).

Cost estimate: The CO2 abatement cost of this method is equal to USD 106.16 per tonne of CO2, which is considered a worthwhile investment. The most important factor in the mitigation cost is transportation rates. The transportation current rate is USD 0.092 per tonne per Km but if it increases, the abatement cost will also increase accordingly.

3.1.3.3 Chemical manufacturing

Chemical industry is central in the European manufacturing sector, providing innovative materials and technological solutions to enhance Europe's industrial competitiveness. It encompasses the production of various chemicals, such as petrochemicals, polymers, inorganics, specialties, and consumer chemicals.

Despite facing challenges like increased competition and rising costs, the industry has demonstrated resilience by recovering quickly from economic crises and maintaining stable total sales. The industry's competitiveness contributes to improved living standards, job creation, and wealth generation. It fuels innovation and development across the entire economic system while addressing societal challenges and supporting other sectors.

Here are some notable statistics about the EU chemical industry:

- It represents approximately 7.5% of EU manufacturing turnover.
- It generates an annual revenue of EUR 565 billion, corresponding to around 17% of global chemicals sales.
- It provides 1.2 million direct highly skilled jobs (2015) and supports an estimated 3.6 million indirect jobs, with a total impact on around 19 million jobs throughout the value supply chains.
- It exhibits a labour productivity that is 77% higher than the manufacturing average.
- It generates a trade surplus of EUR 45 billion (2018).

The chemical industry serves as a crucial component of the EU manufacturing industry, with 56% of EU chemicals sold to downstream users being utilised by other industrial sectors. Additionally, it maintains significant links with agriculture and services. The sector's strong focus on innovation positions it as a solution provider for various societal challenges, including climate change, health, and nutrition.

Furthermore, the chemical industry is fostering new forms of collaboration with other sectors to support European manufacturing jobs such as for the production of bioplastics. The industry also plays a vital role in driving resource and energy efficiency efforts. Overall, the chemical industry is an integral part of Europe's manufacturing landscape, contributing to economic growth, employment, innovation, and sustainability[30].

In 2019, the chemical industry, which produces items like plastics, rubber, fertilisers, solvents, food additives, and pharmaceuticals, was responsible for emitting between 1.1 and 1.7 gigatonnes of CO2 equivalent, equal to 10% of global direct industrial emissions (Verdolini et al. 2023).

Fuel switching and electrification, particularly in ammonia production, can significantly reduce emissions. Future low-carbon alternatives for ammonia include methane

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[30] https://single-market-economy.ec.europa.eu/sectors/chemicals_en

pyrolysis, hydrogen from electrolysis powered by green energy, and natural gas reforming with CCS. Circularity practices, including the pyrolysis of used plastics to produce alternative fuels for steam crackers, chemical recycling methods, and combining chemical recycling with CCS, are strategies towards near-zero emissions. Demand-side strategies like improving end-use efficiency, enhancing material efficiency, and curbing demand growth are essential alongside recycling to reduce primary production needs. In what follows we introduce some of the most innovative and promising decarbonization methods for chemical manufacturing.

Feedstock recycling

Chemical recycling offers a promising alternative to conventional treatment methods for non-biodegradable carbonaceous waste which mainly include material recycling and thermal treatment. The efficiency of conventional material recycling in particular, is limited due to the declining quality of recycled output in each cycle. Chemical recycling methods, in contrast, involve various processes that use chemical reactions to transform carbonaceous waste fractions (like plastics or food scraps) into valuable new materials (Seidl et al. 2021). These processes can be adapted to different types of waste, depending on the desired end product and the specific chemical conversion method employed. Two main methods of chemical recycling include pyrolysis process for the conversion of mixed plastic-rich waste to liquid oil, and gasification of a broad range of carbonaceous feedstock for the production of synthesis gases. The main difference between these techniques and conventional material recycling is that their output is not recovered plastic components but chemical feedstock that can be used again in the chemical production process. Currently about 60% of all operating chemical recycling capacity in Europe adopts the pyrolysis method to recycle mixed plastic waste[31].

Potential GHG reduction: Although chemical recycling is currently more costly, it aims to recover more materials and carbon than traditional methods, thus ultimately resulting in a reduction of fossil fuels consumption and GHG emissions. A life-cycle analysis of these methods in the context of Germany shows that the feedstock recycling can reduce GHG emissions by 0.30 to 1.33 kg CO2eq per kg waste feedstock depending on the source of energy (renewable or natural gas) compared to conventional waste incineration and chemical production (Keller 2023).

Cost estimate: For a chemical recycling plant with the capacity of 300,000 tonnes of plastic waste per year and under current market conditions in terms of energy mix supply, prices, and regulations in Germany, the total capital cost is estimated at EUR 420 million compared to EUR 180 million for a direct incineration plant of the same capacity (Voss, Lee, and Fröhling 2022).

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[31] https://www.plasticstoday.com/advanced-recycling/icis-now-tracks-pyrolysis-oil-pricing-for-chemical-recycling

Low carbon feedstock

Although general methods and technologies such as electrification and fuel switching provide promising scope for the chemical sector decarbonization, it is still very likely that such efficiency gains are not enough to reach the net zero targets. As a result, the industry might consider alternative fuels and feedstocks. As an example, bio-based feedstocks and fuels could potentially provide an alternative despite their limited supply due to the amount of available land and insufficient storage and transport infrastructure. Recycled fuels and feedstocks, as discussed above, can offer the dual benefit of providing GHG emissions reductions by reducing the dependency of the chemical process on virgin materials while addressing the issue of plastic waste in the environment. There are different types of bio-based feedstocks that can replace crude oil in chemical processes. The most common forms are polysaccharides and triglycerides, but they can also consist of simple mixed organic waste streams. In this case, bio-based polymers are produced directly through the fermentation of organic waste streams (Sheldon and Brady 2022).

Potential GHG reduction: Unveiling the actual GHG reduction potential of bio-based products depends on several factors including the global bio-economy's scale and structure, and critically, its impact on land-use change emissions, which are often missing from bio-product assessments. Nevertheless, it is estimated that bio-based feedstock can reduce GHG footprint of chemical manufacturing by 45% on average and across different feedstocks (Zuiderveen et al. 2023).

Cost estimate: A meta-analysis of the costs of producing the bio-based polymer polylactic acid (PLA) from different feedstocks shows a wide range from 844 to 3,558 USD per ton of PLA with costs for raw materials, energy, labour and capital being identified as the main cost drivers (Wellenreuther, Wolf, and Zander 2022).

Fuel switching for ammonia production

Ammonia is primarily produced through the energy-intensive Haber-Bosch process, utilising hydrogen from natural gas steam reforming. This conventional method contributes significantly to global GHG emissions, with approximately 1.5 kg CO2/kg NH3 released during ammonia production. In response to climate change threats, the EU has set ambitious carbon reduction targets, prompting a shift towards renewable fuel sources in industrial processes. One potential solution, alternative to natural gas, is biomass gasification for syngas production in ammonia synthesis.

Potential GHG reduction: Preliminary findings indicate that compared to conventional steam reforming, a significant net energy saving of 27.7 MJ/kg NH3 and a CO2eq reduction of 1.09 kg CO2eq/kg NH3 are possible. Although these estimates consider factors such as biomass cultivation, gasification, and transportation, further refinement through techno-economic assessment (TEA) and life cycle analysis (LCA) is needed to have a better understanding of the GHG reduction potential of such techniques (Gilbert and Thornley 2010).

Green methanol production

Currently, natural gas is the dominant feedstock used for the production of about 80% of methanol in the world, where methane (CH4) reacts with H2O at high temperature and pressure (Iaquaniello et al. 2017). A promising alternative is to convert the CO2 from anaerobic digestion processes and biomass to methanol via direct hydrogenation using renewable energy sources for producing green hydrogen (Ciancio, Mojtahed, and Sgaramella 2023). Figure 13 shows different components of this process. The output product, also known as green methanol (CH3OH or MeOH), is considered an alternative clean fuel with higher volume-specific energy density and relatively easier transport process (Gu et al. 2022) or a green raw material or feedstock for synthetic production of other chemicals including biodiesel (Palone et al. 2023). Therefore, the use of green methanol can contribute to the hard-to-abate sector greening. However, the large-scale commercialization of this method still faces much higher production costs (Battaglia et al. 2021).

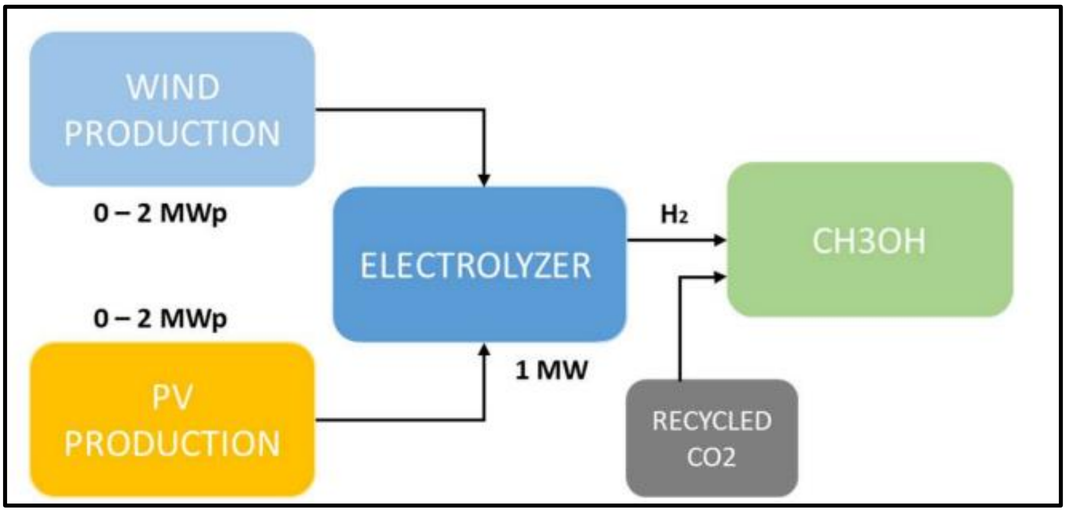

Figure 13: Green methanol production through power-to-fuel process (Ciancio, Mojtahed, and Sgaramella 2023).

Another alternative, called Waste-to-Methanol, is to use Refuse-derived-Fuels (RdF) for the production of green methanol or bio-methanol. In this case, RdF is mixed with oxygen in a high temperature converter in order to produce a syngas (a mixture of carbon monoxide and hydrogen). After purification, the syngas is converted into raw methanol in a reactor (Iaquaniello et al. 2017).

Potential GHG reduction: The Waste-to-Methanol process will have about 40% less GHG emissions than methanol production from fossil fuels and 30-35% less GHG emissions compared to methanol from bio-resources (bio-methanol).

Cost estimate: A techno-economic assessment of this approach in Italy, shows that the current levelized cost of green methanol production can range between EUR 158.41 per MWh and EUR 227.69 per MWh and the production cost of this method is shown to be about EUR 110 per ton for a new 300 ton/day plant (Iaquaniello et al. 2017).

3.2 Agriculture

3.2.1 Key challenges and opportunities

During the COVID-19 crisis, the agriculture and forestry sector emerged as a resilient component of the economy, experiencing minimal disruption in its operational continuity. The direct energy consumption in this sector exhibited marginal variation, recording a slight increase to 28.0 million tonnes of oil equivalent in 2020 compared to 2019. This sector contributed to 3.2% of the overall energy consumption in the EU for the same year as shown in Figure 14. Notably, the Netherlands stood out among EU Member States, with its agricultural and forestry sector constituting the highest proportion (9.0%) of total direct energy consumption. This remarkable share is attributed to the significant role played by glasshouse production in cultivating fruits, vegetables, and horticultural plants. Additionally, Poland and Latvia also demonstrated relatively elevated shares at 5.5% and 5.4%, respectively.

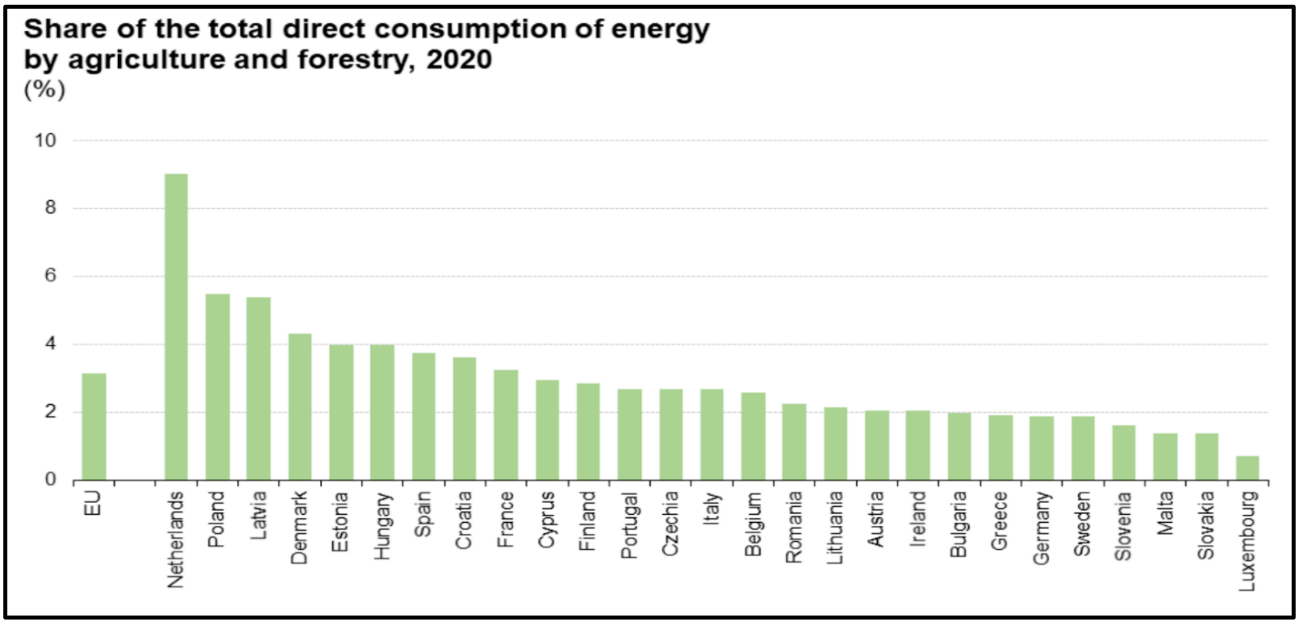

Figure 14: Share of the total direct consumption of energy by agriculture and forestry 2020[32]

Presently, legislative measures pertaining to energy efficiency are undergoing revision to align with the ambitious climate objectives outlined in the 2021 European Green Deal, aiming not only to diminish the EU's reliance on fossil fuel imports but also to mitigate CO2 emissions. The resurgence in the EU's overall energy consumption in 2021, marking a 6.2% increase following the impact of COVID-19 restrictions in 2020, pushed the EU's consumption levels slightly beyond those of 2019.

Notably, the constraints imposed in 2020 did not impede agricultural and forestry activities. Consequently, energy consumption within this sector remained relatively stable when compared to the EU's overall trend. However, divergent patterns were

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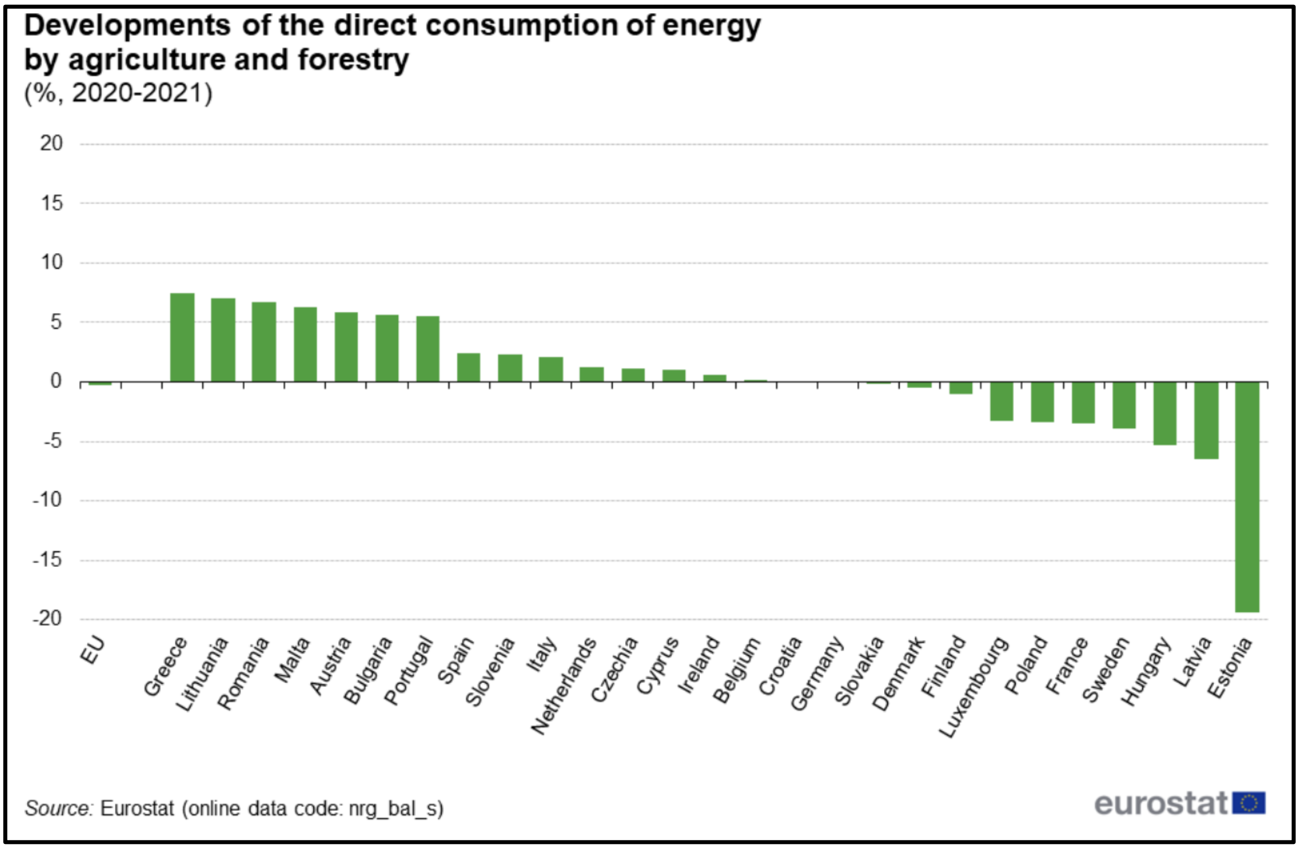
[32] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_energy_use&oldid=322997

observed among Member States, as delineated in Figure 15. Nine Member States exhibited declines in the direct utilisation of energy by the agriculture and forestry sector in 2021, ranging from a marginal reduction of -0.4% in Denmark to a substantial decrease of -19.4% in Estonia. Conversely, noteworthy increases above 5% were observed in Greece (+7.5%), Lithuania (+7.1%), Romania (+6.8%), Malta (+6.3%), Austria (+5.8%), and Portugal (+5.5%).



Source: Eurostat (online data code: nrg_bal_s)

Figure 15: Annual change in total direct consumption of energy by agriculture and forestry from 2020 to 2021[33]

In 2021, oil and petroleum products retained their predominant status as the primary fuel source for direct energy consumption in the agriculture and forestry sector. Within the EU, a substantial majority of the total direct energy consumption in the agriculture and forestry sector (55.9%) was attributed to oil and petroleum products, excluding biofuels. This proportion markedly exceeded the corresponding figure for the entire economy, which stood at 34.8%.

Across most of EU Member States, oil and petroleum products were the predominant fuel type utilised by the agriculture and forestry sector. Nevertheless, noteworthy exceptions were observed. In the Netherlands, for instance, only 11.6% of the total direct energy consumption in the agriculture and forestry sector in 2021 originated from oil and petroleum products. Instead, a majority of 52.2% was derived from natural gas,

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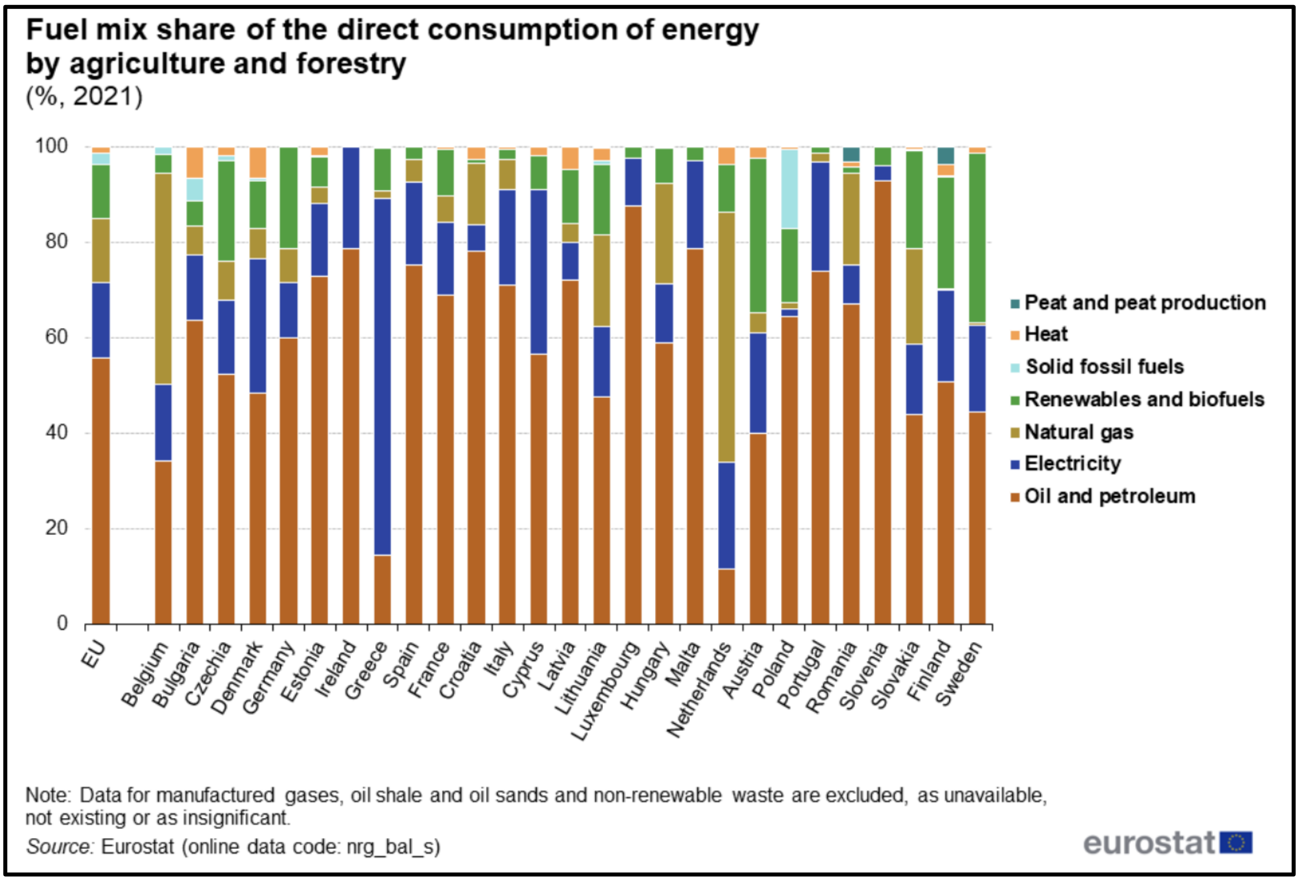
[33] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_energy_use&oldid=322997

and 22.4% from electricity. Greece, on the other hand, stood out with a remarkable 74.8% of the sector's total direct energy consumption sourced from electricity.

In Sweden and Austria, renewable energy sources constituted a significant portion, accounting for approximately one-third (35.6% and 32.3%, respectively) of the total direct energy consumption in the agriculture and forestry sector. Moreover, in Finland, Germany, Czechia, and Slovakia, renewable energy shares exceeded 20%, as illustrated in Figure 16.



Note: Data for manufactured gases, oil shale and oil sands and non-renewable waste are excluded, as unavailable, not existing or as insignificant.

Source: Eurostat (online data code: nrg_bal_s)

Figure 16: Fuel mix share of the direct consumption of energy by agriculture and forestry[34]

When evaluating energy consumption trends across countries, it is imperative to recognize the inherent disparity in total energy consumption levels owing to variations in size. To facilitate meaningful comparisons, a common denominator must be established. The utilised agricultural area (UAA) serves as a widely employed denominator for assessing agri-environmental indicators across countries. Ideally, the chosen denominator should exhibit a robust correlation with the indicator under consideration. In the context of the European Union, the average direct consumption of energy by the agriculture and forestry sector in 2021 amounted to 171 kilograms of oil equivalent per hectare (KgOE/ha). This standardised measure provides a more equitable basis for evaluating and comparing energy consumption patterns, considering the varying sizes of agricultural areas across different countries.

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[34] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_energy_use&oldid=322997

3.2.2 Evaluation of cross-cutting technologies

Since 1990, annual global agri-food system emissions have increased by 17% and they reached 16.5 Gt CO2 eq. in 2019 corresponding to 31% of total GHG emissions from anthropogenic sources (Tubiello et al. 2022). More concerning is the composition of GHG emissions from this sector which is markedly different from CO2 emissions from other sectors such as energy, industry, and transportation. Beside CO2, agricultural GHG emissions are mainly composed of CH4 and N2O with much higher global warming potential. The agricultural emissions alone constitute more than 50 and 75% of total emissions of these two gases (FAO 2021). As a result, climate-smart agricultural practices have been introduced to reduce the negative impact of agricultural practices on the environment while increasing the adaptability of farms, farmers, and their livelihood to the consequences of climate change (Kazimierczuk et al. 2023). These practices can be classified in 3 categories as shown in Figure 17:

Regenerative agriculture (RA) involves a mixture of methods and practices aimed at protecting and enhancing soil health by increasing soil fertility, water retention, and system biodiversity and resilience.

Digital agriculture (DA) involves technological innovations based on data gathering, processing, and analysis for improving the quality and quantity of agricultural outputs.

Controlled environment agriculture (CEA) involves technologies and methods such as vertical farms, greenhouses, container farms, and integrated aquaponic systems which generally reduce dependency on water and land and increase the resilience of farming practices.

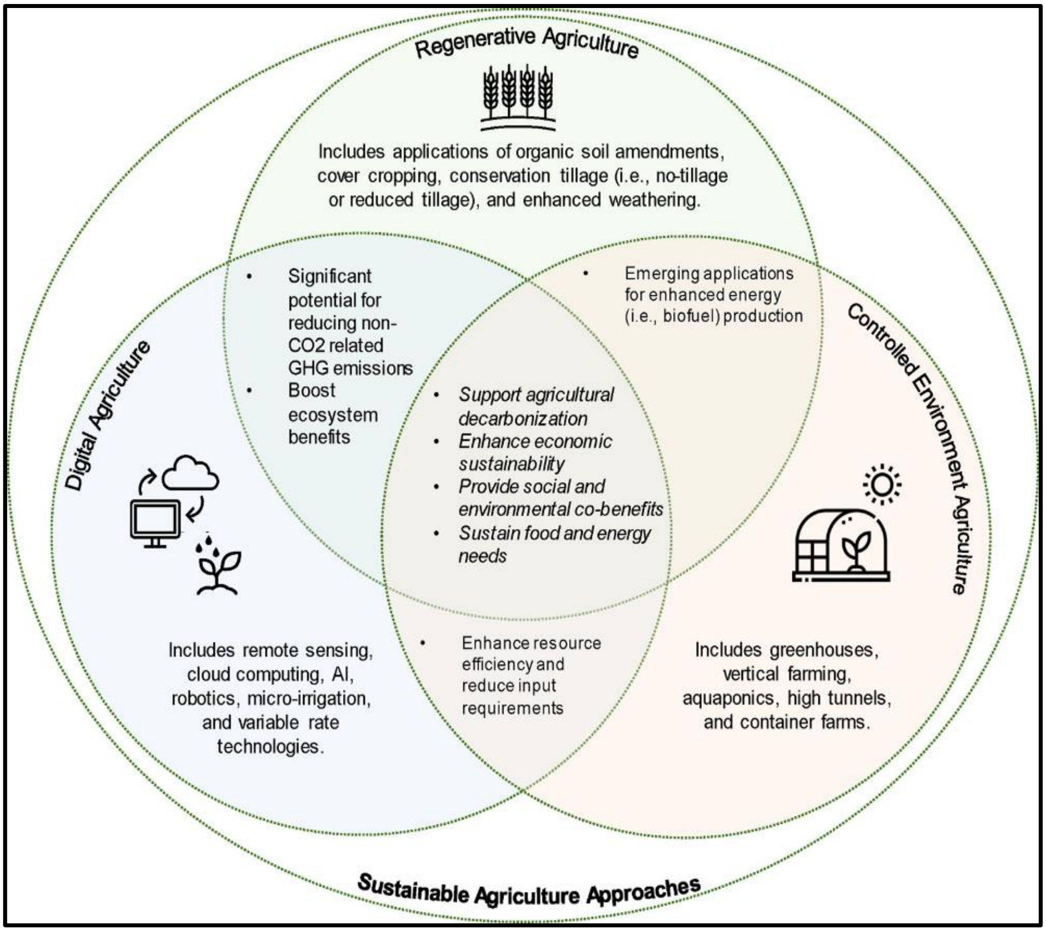

Figure 17: Climate-smart agricultural practices (Kazimierczuk et al. 2023)

A recent report by the National Renewable Energy laboratory (NREL) in the US has explored significant mitigation options for reducing GHG emissions in the agricultural sector (Staie et al. 2024). It identifies specific strategies that offer substantial mitigation potential, each equivalent to at least 10% of annual US agricultural emissions or 73 million metric tons of CO2 equivalent per year (MMT CO2e/yr).

Key mitigation options include:

- Agroforestry (52% or 381 MMT CO2e/yr of GHG mitigation)
- Biochar application (29% or 211 MMT CO2e/yr of GHG mitigation)
- No-till systems (19% or 137 MMT CO2e/yr of GHG mitigation)
- Cover crops (14% or 103 MMT CO2e/yr of GHG mitigation)
- Grazing strategies (12% or 91 MMT CO2e/yr of GHG mitigation)
- Feed additives for livestock (12% or 88 MMT CO2e/yr of GHG mitigation)
- Renewable energy production (including installation of anaerobic digesters) (11%; 79 MMT CO2e/yr of GHG mitigation)

While GHG emissions from soil management and enteric fermentation are significant contributors, finding effective mitigation solutions remains challenging due to their process-based nature. Existing technologies such as enhanced efficiency fertilisers and precision agriculture can mitigate some emissions but not all, emphasising the need for further research in these areas. There's the necessity of substantial carbon sequestration in agricultural soils for achieving significant decarbonization. Practices such as agroforestry, biochar application, and no-till offer promising avenues for carbon sequestration. The potential to offset more GHG emissions through these practices than the agricultural sector currently emits underscores their importance. Despite the potential benefits, current estimates of carbon sequestration potential are uncertain due to variations in soils, climates, agricultural practices, soil organic carbon saturation rates, permanence, and interactions with other sequestration activities.

3.2.3 Evaluation of specific technologies

Biomass for bioenergy with carbon capture and storage (BECCS)

Biomass feedstock for bioenergy with carbon capture and storage (BECCS) is classified as a terrestrial method for carbon dioxide removal (CDR) which plays a key role in decarbonization scenarios to keep the global temperature increase below the 1.5-degree target by 2100 (Minx et al. 2018). However, the heavy reliance of decarbonization pathways on large-scale bioenergy production may threaten the amount of land available for food production and impact the livelihoods of rural communities (Fajardy et al. 2018).

The Renewable Energy Directive defines biomass as the biodegradable fraction of products, waste, and residues from various biological origins, including agriculture, forestry, fisheries, and aquaculture, as well as biodegradable waste from industrial and municipal sources[35]. Despite efforts to estimate agricultural residue production in Europe, methodological shortcomings persist due to the lack of hard data at the EU level and varying assumptions. Dedicated energy crops currently make up a minor fraction (0.1%) of total biomass production, with estimates suggesting cultivation on approximately 50,000 hectares in 2017, primarily in Poland and Sweden. However, this represents only a fraction of Europe's agricultural land. Studies indicate substantial potential growth in this sector, especially considering the availability of abandoned, degraded, and contaminated land suitable for energy crop cultivation. Conservative estimates suggest that around 1.35 million hectares of land in the EU could be further investigated for dedicated energy cropping, potentially expanding cultivation areas by 27 times the current extent. Additionally, cultivating energy crops on unfavourable agricultural land, such as low-productivity areas due to contamination or erosion, could significantly increase potential cultivation areas.

The map in Figure 18 shows the percentage of potentially available land for bioenergy crop production by 2033, highlighting favourable locations for biomass production. Eastern Europe, and to a lesser extent, Southwest Europe, emerge as promising regions for biomass production.

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[35] https://oeil.secure.europarl.europa.eu/oeil/popups/ficheprocedure.do?lang=en&reference=2016/0382(COD)

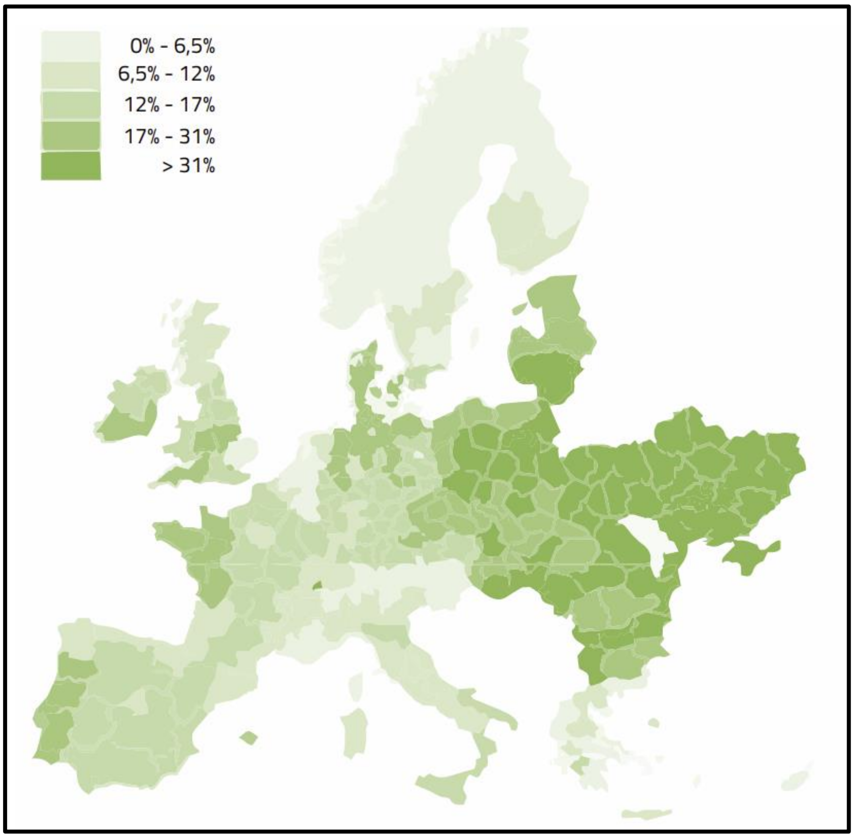

Figure 18: Percentage of potentially available land for bioenergy crop production by 2033[36]

As Figure 19 shows, out of about 1 billion tonnes of available biomass in the EU, more than half is used for food while only 20% is used for energy production.

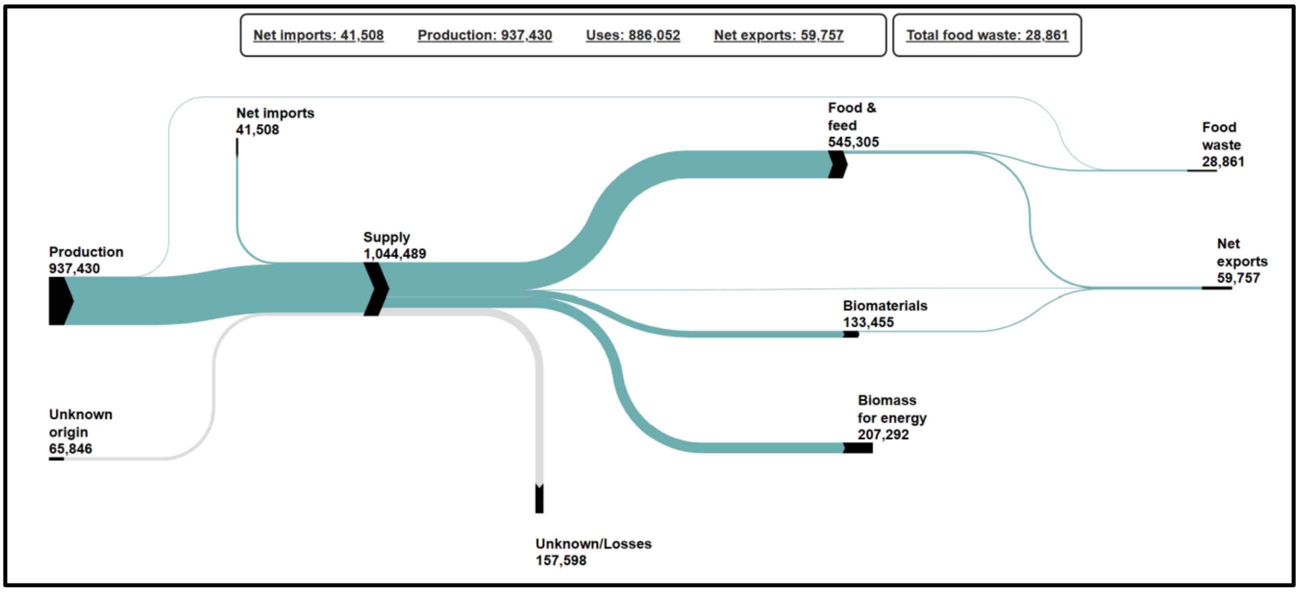

Figure 19: Biomass flows in 1000 T of dry matter (net trade) in the EU[37]

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[36] https://bioenergyeurope.org/article/204-bioenergy-explained-biomass-for-energy-agricultural-residues-energy-crops.html

[37] https://datam.jrc.ec.europa.eu/datam/mashup/BIOMASS_FLOWS/index.html

Bioenergy with Carbon Capture and Storage (BECCS) represents a pioneering approach that seamlessly integrates renewable energy production with carbon dioxide removal. This innovative technology holds immense promise in the fight against climate change. BECCS involves capturing CO2 emissions originating from biogenic sources, such as biomass combustion or biofuel generation. The captured CO2 is then securely stored, preventing its release into the atmosphere. Typically, this storage occurs deep within geological formations, where the CO2 mineralizes over time (Figure 20). BECCS not only serves as a potent carbon removal mechanism but also generates valuable energy. Biomass, which actively absorbs CO2 during its growth, serves as the primary feedstock. By capturing the biogenic carbon from biomass, BECCS significantly reduces atmospheric CO2 levels. Furthermore, the stored biogenic CO2 can be harnessed as a valuable resource. Indeed, it finds applications as a foundational component in the chemical industry and other material sectors.

Biochar on the other hand, complements the BECCS concept by offering additional environmental advantages. Biochar results from the thermochemical transformation of biomass. During this process, biomass undergoes controlled heating in the absence of oxygen, yielding a stable form of carbon. Unlike raw biomass, biochar remains resistant to microbial degradation. Biochar finds use in water treatment systems, effectively removing impurities and contaminants. When incorporated into soil, biochar improves aeration, enhances water retention, and boosts nutrient availability. Alternatively, biochar serves as a sustainable alternative in construction materials.

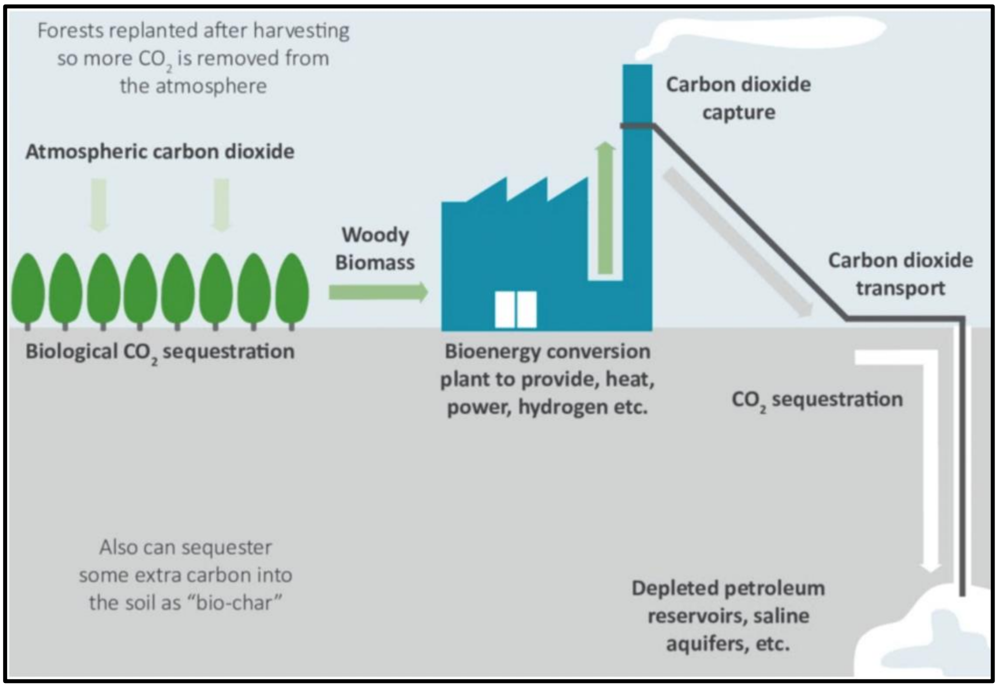

Figure 20: Biomass with carbon capture and storage[38]

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[38] https://earth.org/bioenergy-with-carbon-capture-and-storage-a-silver-bullet-for-carbon-emissions/

Potential GHG reduction: The effectiveness of large scale BECCS projects in combating climate change is yet to be proven in practice. The Paris climate agreement highlights the need to remove around 20 billion tons of CO2 annually by 2100 to limit global temperature rise, but BECCS might only remove three to five billion tons per year. Moreover, BECCS requires substantial land and time, necessitating significant allocation of agricultural, forestry, and municipal waste resources. Implementing BECCS at scale could require up to 40% of global cropland, leading to biodiversity loss, reduced food availability, and potential increases in food prices[39].

Cost estimate: While BECCS could be scaled up to store large amounts of carbon for less than USD 100 per tonne, it may not sufficiently address climate change impacts.

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[39] https://psci.princeton.edu/tips/2020/11/15/preventing-climate-change-with-beccs-bioenergy-with-carbon-capture-and-storage

Agrivoltaics

Agrivoltaics, also known as agrophotovoltaics, is a sustainable approach that involves utilising land for both agriculture and solar energy production simultaneously (Figure 21). The combination of solar panels and crops in agrivoltaics, results in optimised land use (Dupraz et al. 2011). This concept encompasses various methods, ranging from conventional solar panels placed above crops to greenhouses constructed with semi-transparent photovoltaic panels. By integrating solar panels into agricultural spaces, agrivoltaics enables farmers to optimise land use, enhance crop yields, and generate additional income streams. The design of agrivoltaics systems may involve trade-offs between maximising crop yield, crop quality, and energy production, as both solar panels and crops need access to sunlight. However, the partial shade provided by the solar panels can mitigate some stress on plants caused by high temperatures and UV damage, potentially resulting in increased crop yields. Moreover, agrivoltaics can lead to benefits such as greater land productivity, reduced water consumption for irrigation due to shading from the photovoltaic modules, and additional income opportunities for farmers, which can contribute to the competitiveness and sustainability of agricultural businesses. Collaboration between farmers, agronomists, agricultural firms, and other stakeholders within the sector can further enhance the value creation and shared benefits of agrivoltaics across regions.

A typical Agrivoltaics system consists of installing solar panels above or between crops. Agrivoltaics can be classified along four dimensions: (1) the system used, (2) the PV structure, (3) the farming type, and (4) the flexibility (Jain et al. 2021). Regarding the system used, Agrivoltaics categorization includes open or closed systems. The former involves positioning panels over or between crops, while the latter employs PV installation on greenhouses. For what concerns the PV structure, the first technique is the installation of panels at 2-5 metres in height, leaving space for crops to grow beneath, while the second technique is represented by the installation of PV at ground level, leaving space for the crops in between. The farming type classification distinguishes between crop farming, involving low-economic value products like potatoes and rice using crop rotation systems, and orchard farming, which cultivates fruits or nuts in a geometric layout. Flexibility refers to static or dynamic systems. Dynamic systems incorporate solar panels capable of tracking sunlight for increased efficiency or improved microclimates for crops underneath. Static systems, on the other hand, use fixed solar panels.

Apart from increased efficiency due to the dual land use, Agrivoltaics can potentially increase crop productivity by providing the right amount of sunlight exposure. Furthermore, the shadow provided by the panels can reduce water evaporation achieving from 14% to 29% water savings (Roxani et al. 2023). From a financial point of view, the combination of solar panels and crops can increase the entire field productivity (considering the energy generation) by 70%. As a drawback, not all crops can benefit from shading, limiting the range of choice for the farmer. In fact, there is still little research on crop performance and yields, leading to an increase in uncertainty for potential investors. Furthermore, the high initial cost of capital requires subsidies or incentives from the government to make this technology available to small farmers.

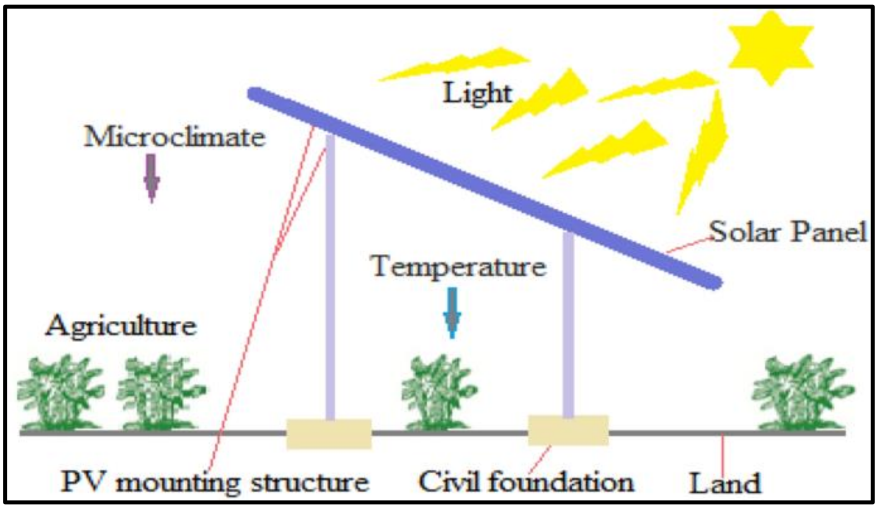


Figure 21: Design of an agrivoltaics system (Giri and Mohanty 2022)

To better understand the advantage of using agrivoltaics, a research study was conducted at the Chonnam National University in South Korea. This study was focused on the co-benefit of producing solar power on broccoli and cabbage growing through the shade provided by photovoltaic facilities as shown in Figure 22. It showed that agrivoltaic shading can result in greener broccoli with no significant difference in yield and antioxidant capacity, compared to open-field broccoli (Chae et al. 2022).

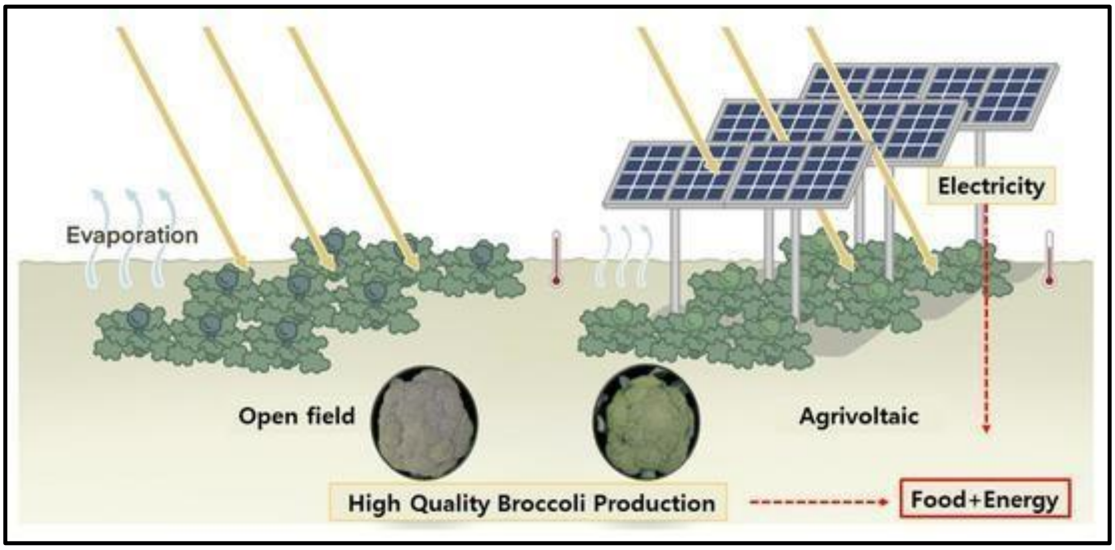


Figure 22: Agrivoltaics for joint energy and broccoli production in South Korea (Chae et al. 2022)

Potential GHG reduction:

Agrivoltaics systems are being explored in the Philippines to boost renewable energy adoption and cut carbon emissions in the power sector. Given the country's vast rice farming areas and unique geography, batteries are being considered as an alternative to expanding transmission lines. Through linear programming, a model optimised the power generation mix, considering generator and transmission line capacities across the country. Simulation results show that integrating agrivoltaics and/or batteries could significantly contribute to the energy mix, potentially reducing carbon emissions. For example, using 1% and 10% of agrivoltaics in rice farmlands could generate 11.04 TWh and 95.75 TWh, respectively. Combining batteries with 10% agrivoltaics could lead to an 85% reduction in carbon emissions, surpassing official targets. This study is the first to comprehensively analyse large-scale agrivoltaics integration into the Philippine power sector, offering valuable insights into its feasibility and benefits (Gonocruz et al. 2023).

Cost estimate:

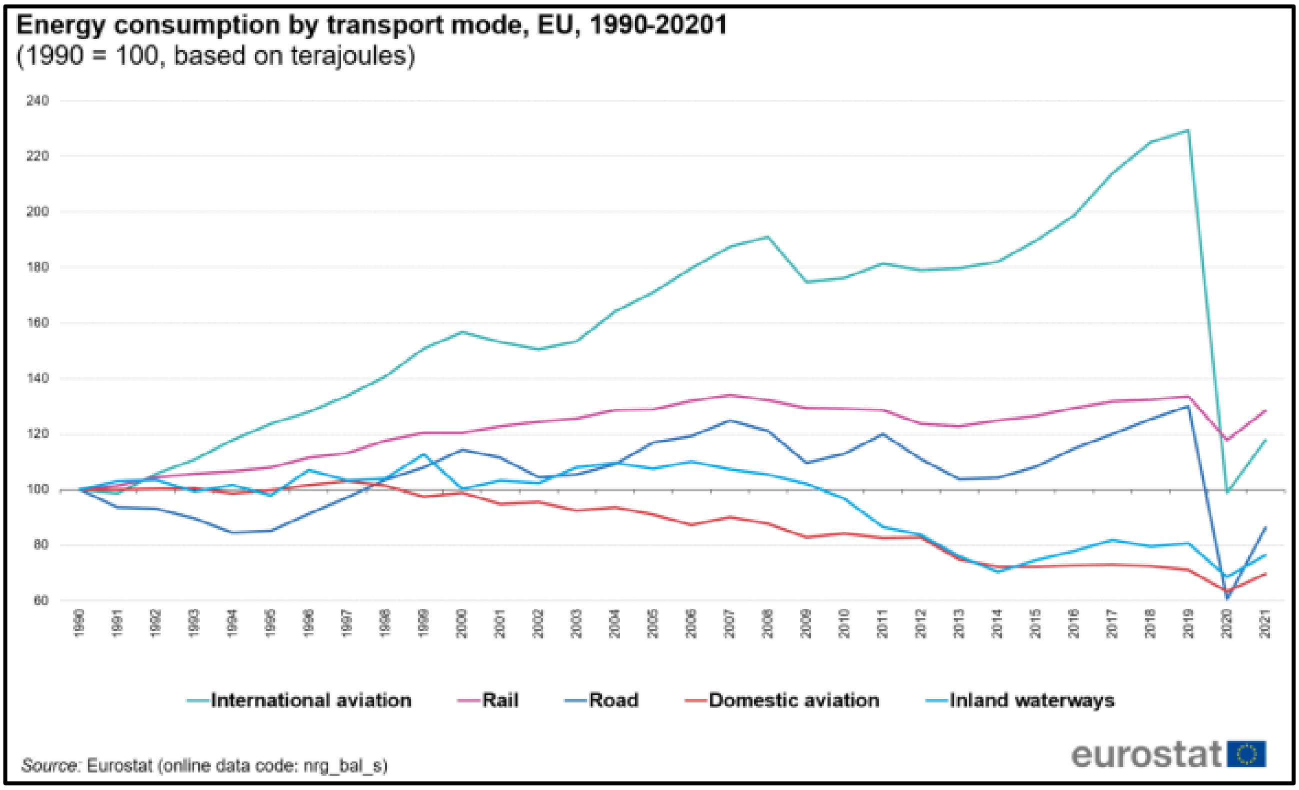
The economic estimates from an Agrivoltaics project in Germany show that the Agrivoltaics costs are much higher than traditional farms. For example, the total cost of an elevated module Agrivoltaics system with a capacity of 650kW is estimated at EUR 1,234/kW, bringing the total investment at EUR 80,210/hectare, compared to the EUR 572/kW needed for a ground-mounted plant. Moreover, Agrivoltaics systems need strong subsidies such as feed-in tariffs to be profitable (Trommsdorff 2016). Another study from blueberry farms in Chile has found that the Agrivoltaics co-benefits from the provided shade alone is not enough to justify their higher capital cost compared to traditional plastic net covering (Jung and Salmon 2022).

3.3 Transportation

3.3.1 Key challenges and opportunities

The energy consumption of transport grew by 9.3% in 2021, reaching 277 Mtoe at the EU level. It follows a sharp decrease in 2020 (-13%) due to the impacts of COVID crisis. Previously, it grew from 2014 to 2019 following the economic growth rebound (+1.7%/year), which contrasts with the previous period impacted by the economic crisis (-1.5%/year from 2007 to 2013). In 2021, the energy consumption of transport of the EU was 5% below its pre-COVID level and 5% above its 2000 level (Figure 23).

Road transport absorbs almost 94% of the final energy consumption of transport (excluding international air) in the EU (range 70-100%). Specifically, the share of road transport at the EU level slightly increased between 2000 and 2019 (+1.4 percentage point), with an increasing share in 3/4 of EU countries.



Source: Eurostat (online data code: nrg_bal_s)

Figure 23: Energy consumption in the transportation sector in the EU[40]

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[40] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview&oldid=616454#Final_energy_consumption

3.3.2 Evaluation of cross-cutting technologies

Decarbonization of private transport

The transportation sector is a significant contributor to global greenhouse gas emissions, primarily through the combustion of fossil fuels in road vehicles, aviation, shipping, and rail transport. As the world strives to limit global warming to well below 2 degrees Celsius, decarbonizing transportation is very important. In the context of private transportation, multifaceted strategies can be explored to reduce emissions effectively (Lah, Fulton, and Arioli 2019):

- Switching to lower-emitting transport modes such as pedestrian and cycling modes by encouraging walking and cycling as viable alternatives to motorized transport reduces emissions significantly. Thus, investments in pedestrian-friendly infrastructures, safe cycling lanes, and urban planning prioritizing non-motorized modes are essential.
- Transitioning from internal combustion engine (ICE) vehicles to electric vehicles (EVs) through incentives, charging infrastructure, and research and development. EVs offer zero direct emissions, especially when powered by renewable energy sources.
- Enhancing the efficiency of conventional vehicles by optimizing engines, reducing weight, and improving aerodynamics.
- Promoting hybrid technologies and alternative fuels (e.g., biofuels, hydrogen) contributes to emission reduction.

Among these technologies and solutions, battery-electric vehicle (BEV) and fuel-cell vehicle (FCEV) technologies are the most promising (Arlango 2022).

Decarbonization of public transport

Public transport heavily relies on fuel-engine buses, which are significant contributors to harmful emissions. Decarbonization efforts primarily target reducing emissions from diesel-fueled bus fleets in urban areas. The EU's clean vehicle directive mandates the procurement of low and zero-emission public transport vehicles, providing a legislative framework for decarbonization initiatives. Public transport operators must proactively plan the transition of their fleets to cleaner energy sources.

Switching to electric vehicles offers benefits such as reduced emissions and noise pollution. However, several challenges hinder the introduction of clean-powered vehicles to public transport. These include longer charging times and shorter ranges compared to combustion engine buses, necessitating adjustments in vehicle scheduling and network design. Additionally, ensuring well-planned charging infrastructure and selecting appropriate battery sizes is crucial. Training public transport staff to handle high-voltage operations is also necessary for successful implementation of electric buses[41].

Decarbonization of heavy transport

As many regions aim for reducing greenhouse gas emissions by mid-century drastically, the focus shifts to the considerable challenges of decarbonizing heavy transportation. Despite advancements in other sectors, transportation remains a significant contributor to global emissions, with liquid fuels derived from oil dominating the industry due to their convenience and high energy density. Decarbonizing transportation varies in difficulty across different vehicle types, with smaller vehicles being more easily electrified compared to heavier counterparts.

Medium and heavy-duty trucks present a significant challenge in decarbonization, with electrification being more feasible for vehicles operating on set routes within limited areas, such as city buses and urban delivery vehicles. However, challenges arise for longer distances and heavier loads due to battery weight and the need for high-power charging infrastructure. For aviation and maritime shipping, which are the most and least greenhouse gas-intensive forms of transport respectively, the challenge lies in their heavy loads and infrequent refuelling opportunities.

To address these challenges, low carbon fuels that can be blended with existing fuels show promise, allowing progress despite the long lifespans of vehicles and vessels. Advanced biofuels and technologies like carbon capture may offer additional solutions, although many of these technologies are costly and unproven at scale. Policymakers face the challenge of aligning technology advancements with policy, while uncertainties such as the COVID-19 pandemic may further complicate transportation preferences and demand[42].

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[41] https://www.ptvgroup.com/en/application-areas/public-transport-planning/decarbonization

[42] https://www.brookings.edu/articles/the-challenge-of-decarbonizing-heavy-transport/

3.3.3 Evaluation of specific technologies

Electric vehicles

A Battery Electric Vehicle (BEV) is an electric vehicle (EV) that relies on the energy stored in its battery to power the electric motor, unlike other vehicles that use internal combustion engines (ICE) or hydrogen fuel cells in addition to the battery for propulsion (Kamran 2023). To estimate the maximum potential energy storage capacity provided by EV batteries, we can assume a scenario in which the cars fleet in Europe (246 million vehicles, 0.465 per population of 529 million people) is transformed into BEV with an average energy storage capacity of 50 kWh and charging capacity of 11 kW. We can further assume that the charging efficiency is 90. Hence, the total available EV batteries' energy storage capacity contributing to the power system operation can be estimated at 6.1 TWh which is roughly equivalent to 19 times the average electricity demand or average hourly load. Especially for passenger cars, SUVs, and pick-up trucks, electrification of vehicle transport remains the primary strategy for decarbonization. Electric vehicles are more efficient users of energy than combustion vehicles, and electricity is easier to decarbonize.

To facilitate the widespread adoption of electric vehicles, accelerating the development of charging infrastructure is important. While initial BEV buyers predominantly relied on private charging, future EV owners, especially those living in multifamily houses without private chargers, will increasingly rely on public charging. Regulatory processes for installing chargers, both in private houses and public spaces, need to be simplified, and production capacity for charging equipment must be increased. It's estimated that more than 15,000 chargers per week will need to be installed within the EU by 2030. Simplified regulations are necessary to expedite charger siting, as current approval processes can take up to three years. Ensuring widespread coverage of public charging locations across the EU is essential to prevent chargers from being concentrated only in profitable areas (Figure 24).

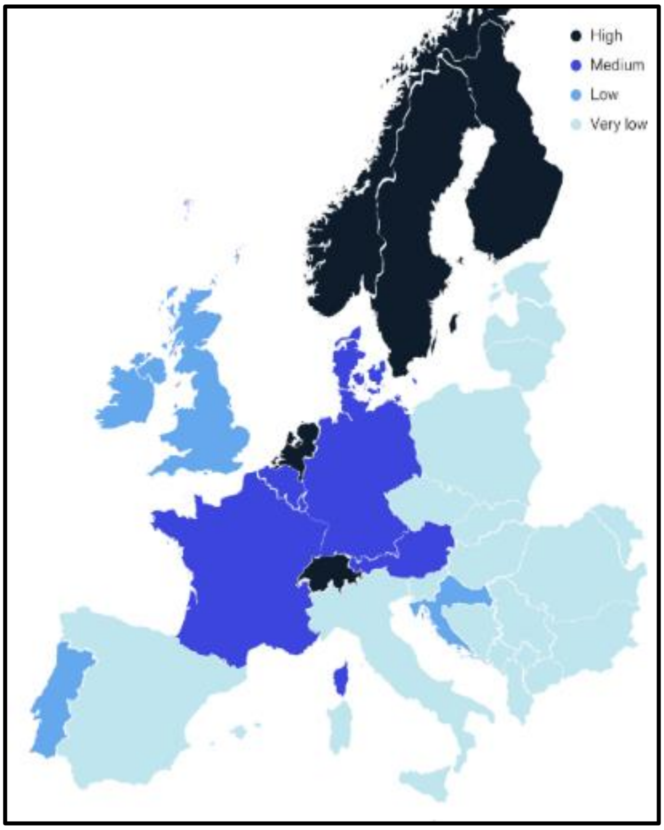

Figure 24: BEV charging infrastructure buildup in Europe[43]

By 2030, BEVs are projected to account for over 5 percent of electricity demand in Europe. To manage the impact on the electric grid, strategies such as "managed charging" through vehicle-to-grid (V2G) technology will be crucial. This involves controlling charging time, duration, and intensity to reduce strain on the grid, particularly during peak load periods. With proper management and incentives for off-peak charging, the strain on the electric grid caused by EV charging can be significantly mitigated.

Potential GHG reduction: Deep decarbonization pathways typically estimate more than 95% of light-duty vehicles being fuelled with electricity by mid-century. There will be almost a complete plug-in electric vehicle (PEV) penetration of new vehicle sales by 2035. The 2021 National Academies report on deep decarbonization stated that in a likely decarbonization path for the United States, the share of electric vehicles would be 50% of the new vehicle sales (light, medium, and heavy duty) by 2030. Additionally, the build-out of the electric vehicle charging infrastructure should accelerate leading to a national network of 120,000 fast chargers by 2030 (National Academies of Sciences, Engineering, and Medicine 2021).

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[43] https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/why-the-automotive-future-is-electric

Low carbon fuels

Low Carbon Fuels (LCF), both liquid and gaseous, are classified based on the renewable raw material used. This includes (1) traditional biofuels from vegetable oils obtained through fermentation of plants containing sugars and starch, (2) advanced biofuels from organic waste materials, (3) recycled carbon fuels from mixed waste and reuse of non-recyclable plastic waste (plasmix), and (4) e-fuels (synthetic fuels) obtained from the synthesis of renewable hydrogen and CO2, either from the atmosphere or more preferably from concentrated sources.

These products result in a CO2 reduction in their life cycle compared to their fossil counterparts, ranging from a minimum of 40% to over 80% for advanced biofuels and over 90% for e-fuels, depending on the raw material used. Additionally, several refineries are working on projects aimed at using or producing "green hydrogen”. This offers the dual benefit of reducing emissions from fuels and other refinery products while also enabling the storage of renewable electricity generated in excess when the supply exceeds the demand. This technology has the potential to strengthen the position of the European refining industry as a leader in deploying future low-carbon solutions such as Power-to-Liquid (PTL) and hydrogen (H2) for mobility.

The development of alternative fuels is also a sector of great interest for companies operating in logistics and distribution. Projects are underway for an alternative fuel consisting of methanol derived from natural gas and ethanol from renewable sources (subsequently blended with petroleum components from refineries).

In product distribution, some retail outlets are offering a wide range of alternative fuels and energies to consumers. Moreover, they are using self-produced renewable energy to make these retail outlets energetically and carbon-neutral. The goal is to transform them into true "Mobility Energy Retail Points"[44].

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[44] https://www.cummins.com/news/2021/10/28/what-are-low-carbon-fuels

Hydrogen fuel cell vehicles

Fuel Cell-based Hybrid Electric Vehicle (FCEV) consists of a technology that improves the BEV concept allowing increased driving ranges and reduced recharging time. FCEV works thanks to a hydrogen fuel cell that runs a traction system working together with a battery (Waseem et al. 2023). Specifically, FCEVs do not rely on a battery to obtain the needed energy, but on a fuel cell that generates electricity using hydrogen.

The primary advantage of the FCEV is the reduction of local emissions or eventually, overall emissions, if the hydrogen is produced through a renewable energy electrolysis process, or through natural gas combined with carbon capture technologies. Moreover, widespread diffusion of this technology could lead countries to reduce their oil and other fossil fuels dependence, since hydrogen can be obtained by water electrolysis. FCEVs have all the advantages of ICE vehicles, such as performance and refilling time, without contributing to carbon emissions. Still, fuel cells are expensive and represent a burden in the vehicle's final price. Current cost estimates for producing 500,000 volumes of fuel cells per year is USD 45/Kw, with the goal set by the U.S. Department of Energy to reach USD 30/Kw. Furthemore, the hydrogen storage and diffusion system are an obstacle to the wide spreading of this technology. In fact, storing hydrogen at high pressure and at low temperatures increases energy density but requires robust, costly tanks. Moreover, it can present safety concerns, and demands significant energy. Other barriers to the FCEV diffusion are the durability and reliability compared to the ICE vehicles. Tests made on 230 vehicles FCEV fleets have experienced a 10% loss of performance between 2,000 and 3,000 hours of operation, while the target to be competitive with ICEVs is 5,000 hours or about 150,000 miles (Kurtz et al. 2019).

Hydrogen-powered fuel cells boast over double the efficiency of traditional combustion methods while emitting zero pollution or greenhouse gas emissions. Currently, there are approximately 11,200 hydrogen-powered cars and 20,000 hydrogen forklift trucks in operation in the US. However, the widespread adoption of hydrogen fuel faces challenges such as the need for specialized fuelling systems and infrastructure. In the United States, there are 60 hydrogen refuelling stations, with 40 open to the public. Liquid hydrogen or ammonia, with their high energy density, hold promise for heavy-duty transportation like long-haul trucks and shipping, although the commercialization of hydrogen planes remains in the early stages. Overcoming technical barriers, including component cost and performance enhancements, and establishing necessary infrastructure, such as refuelling stations, are crucial steps for making hydrogen a significant player in the transportation sector[45].

Fuel cell electric vehicles (FCEVs) utilise hydrogen (H2) as their primary fuel source, distinguishing them as zero-emission vehicles (ZEVs). Like battery electric vehicles (BEVs), FCEVs operate with electric motors instead of internal combustion engines for propulsion (Figure 25). However, while BEVs rely on plug-in rechargeable batteries,

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[45] https://www.energypolicy.columbia.edu/publications/hydrogen-fact-sheet-uses-low-carbon-hydrogen/

FCEVs generate electricity onboard through the utilisation of hydrogen. This process results in the emission of only water and heat as byproducts, making FCEVs environmentally friendly. Hydrogen can power various fuel cell electric applications, with its conversion to electricity emitting no pollutants harmful to public health and reducing GHG emissions, thereby mitigating climate change effects[46].

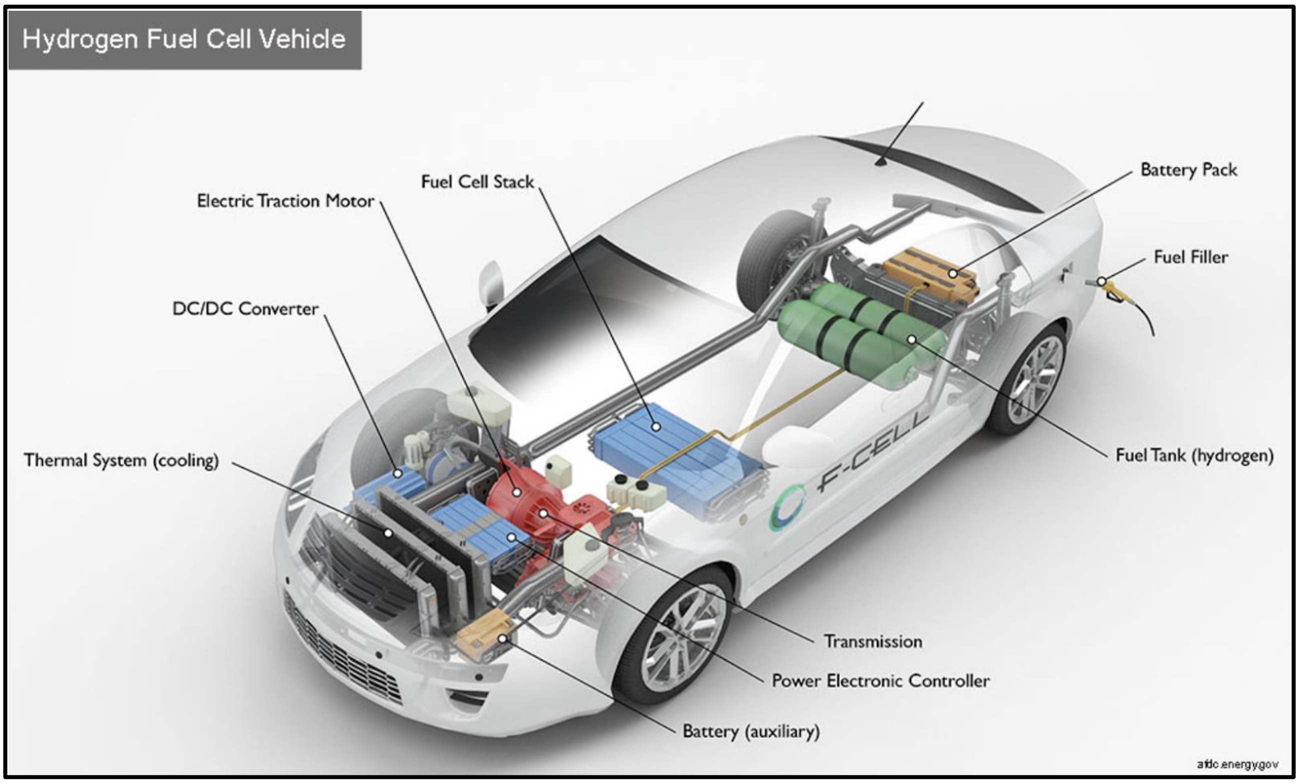

Figure 25: Hydrogen fuel-cell vehicle[47]

Potential GHG reduction: FCEVs, like BEVs, are considered zero-emission vehicles, emitting no smog-related or GHG tailpipe emissions. However, emissions can occur during the production, transportation, and dispensing of hydrogen fuel.

Hydrogen, although abundant, requires separation from other compounds before it can be used as fuel, and this process can be energy-intensive. Currently, most hydrogen in the U.S. is derived from natural gas through steam methane reforming, a process emitting carbon dioxide (CO2) and methane (CH4) if not captured and sequestered. Efforts to reduce CH4 emissions, such as the Methane Emissions and Waste Reduction Incentive Program under the Inflation Reduction Act of 2022, aim to address this issue.

Electrolysis, another common method for hydrogen production, involves splitting water into hydrogen and oxygen using electricity. If the electricity originates from non-emitting sources like solar, wind, or hydropower, there are no upstream GHG emissions. Additionally, capturing and storing CO2 associated with electricity used for hydrogen production can further minimise GHG emissions.

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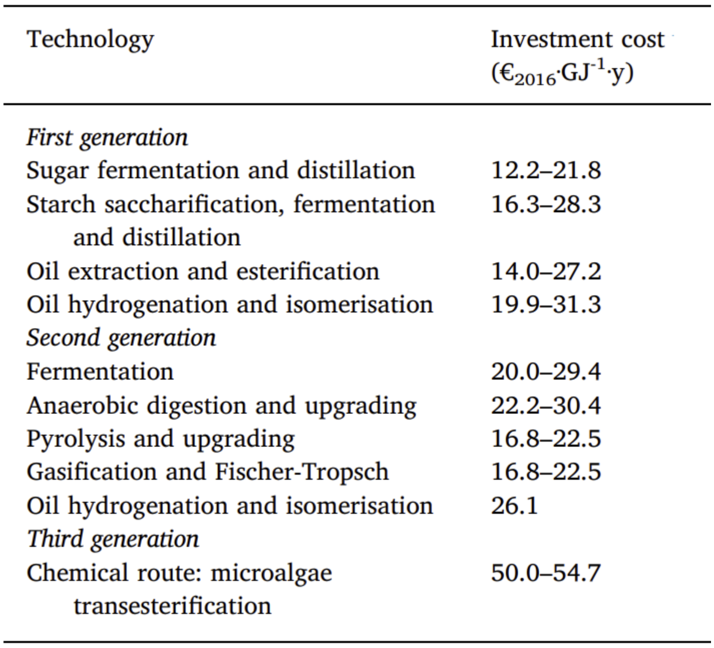
[46] https://www.epa.gov/greenvehicles/hydrogen-transportation

[47] https://afdc.energy.gov/vehicles/how-do-fuel-cell-electric-cars-work

Cost estimate: tables 2 and 3 provide a range of investment cost estimates for different low-carbon fuels including different biofuel and hydrogen production technologies.

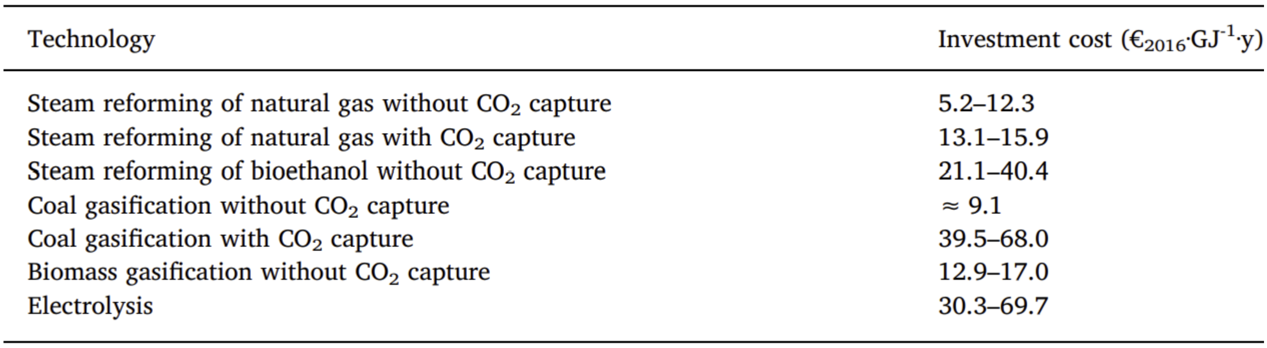
Table 2: Investment cost of biofuel production technologies (Navas-Anguita, García-Gusano, and Iribarren 2019)



Technology	Investment cost ($€_{2016}·GJ^{-1}·y$)
First generation	
Sugar fermentation and distillation	12.2–21.8
Starch saccharification, fermentation and distillation	16.3–28.3
Oil extraction and esterification	14.0–27.2
Oil hydrogenation and isomerisation	19.9–31.3
Second generation	
Fermentation	20.0–29.4
Anaerobic digestion and upgrading	22.2–30.4
Pyrolysis and upgrading	16.8–22.5
Gasification and Fischer-Tropsch	16.8–22.5
Oil hydrogenation and isomerisation	26.1
Third generation	
Chemical route: microalgae transesterification	50.0–54.7

For first-generation technologies, the operation and maintenance (O&M) costs of biofuel production is usually assumed to be around 3-6% of the total investment cost with the production capacity in the range of 300,000-420,000 tonnes. On the other hand, the O&M costs of hydrogen production correspond to 2-5% of the investment cost for electrolysis and 10-13% for other technologies in Table 2.

Table 3: Investment cost of hydrogen production technologies (Navas-Anguita, García-Gusano, and Iribarren 2019)



Technology	Investment cost ($€_{2016}·GJ^{-1}·y$)
Steam reforming of natural gas without CO_2 capture	5.2–12.3
Steam reforming of natural gas with CO_2 capture	13.1–15.9
Steam reforming of bioethanol without CO_2 capture	21.1–40.4
Coal gasification without CO_2 capture	≈ 9.1
Coal gasification with CO_2 capture	39.5–68.0
Biomass gasification without CO_2 capture	12.9–17.0
Electrolysis	30.3–69.7

Autonomous vehicles

Autonomous driving technology aims to revolutionise the automotive industry and reshape the way we experience transportation. Beyond mere convenience, the widespread adoption of autonomous vehicles (AV) holds the potential to unlock substantial value for drivers, the auto industry, and society at large.

One of the most significant impacts of autonomous driving is its potential to enhance safety on the roads. With advanced driver-assistance systems (ADAS) and autonomous features, vehicles can mitigate human error, which is a leading cause of accidents. Studies suggest that the integration of ADAS could reduce accidents by up to 15% by 2030, making roads safer for everyone.

For employees with long commutes, driving an AV might increase worker productivity and even shorten the workday. Since workers can perform their jobs from an autonomous car, they could move more easily farther away from the office, which, in turn, could attract more people to rural areas and suburbs. AV might also improve mobility for elderly drivers, providing them with options that go beyond public transportation or car-sharing services.

From an economic standpoint, autonomous driving represents a significant opportunity for the auto industry. Consumer demand for AD features is evident, with surveys indicating willingness to pay for such technology. As AV capabilities evolve from basic ADAS to fully autonomous systems, there's a projected revenue growth of billions of dollars in the passenger car market by 2035.

The transition to autonomous driving brings forth a revolutionary shift in transportation, promising not only enhanced convenience but also the potential for significant reductions in GHG emissions. While the precise estimations of emission reductions vary, with figures ranging from 40 to 60%, the impact of AVs on environmental sustainability cannot be overlooked. A key driver of potential GHG reductions lies in the transformation of mobility patterns and vehicle ownership models. AVs facilitate shared mobility models such as car-sharing and ride-sharing, which optimise vehicle usage and minimise the need for individual car ownership. By maximising vehicle occupancy and reducing idle time, shared AVs can significantly decrease emissions associated with personal vehicle use.

However, the widespread adoption of shared mobility faces challenges, primarily stemming from societal preferences and behaviours. Convincing individuals to forego the perceived benefits of private car ownership in favour of shared AVs requires innovative strategies. Pricing mechanisms and parking restrictions may prove essential in incentivizing the transition towards more sustainable transportation models, thereby accelerating GHG reductions. Beyond shared mobility, AVs offer a myriad of energy and emission benefits. Factors such as homogeneous traffic flows, reduced highway congestion, and optimised vehicle design contribute to enhanced fuel efficiency and lower emissions. Additionally, AVs streamline parking processes, reducing time spent searching for parking and the need for parking infrastructure, further contributing to environmental sustainability.

Despite these benefits, challenges persist. The potential increase in vehicle size and continuous driving of shared AVs to avoid parking may offset some of the gains, leading to higher energy consumption and emissions. Mitigating these challenges requires thoughtful measures such as programming AVs to drive outside urban areas for parking or optimising routes to minimise energy usage and emissions.

4 Decarbonization examples and regional case studies

In this section, we overview some of the best examples of decarbonization efforts across the EU in different economic sectors. These examples are a testament to the ingenuity of EU businesses and their commitment to the overarching goal of reducing GHG emissions across the EU.

4.1 Examples

4.1.1 Hydrogen direct reduction in steel manufacturing

The Hydrogen direct reduction (H-DR) method in steelmaking (Figure 26) requires approximately 3.48 MWh of electricity per metric ton of liquid steel, primarily due to hydrogen production through electrolysis. Production expenses range from EUR 361 to 640 per tonne of steel, heavily depending on electricity prices and the quantity of steel scraps added to the EAF during the process.

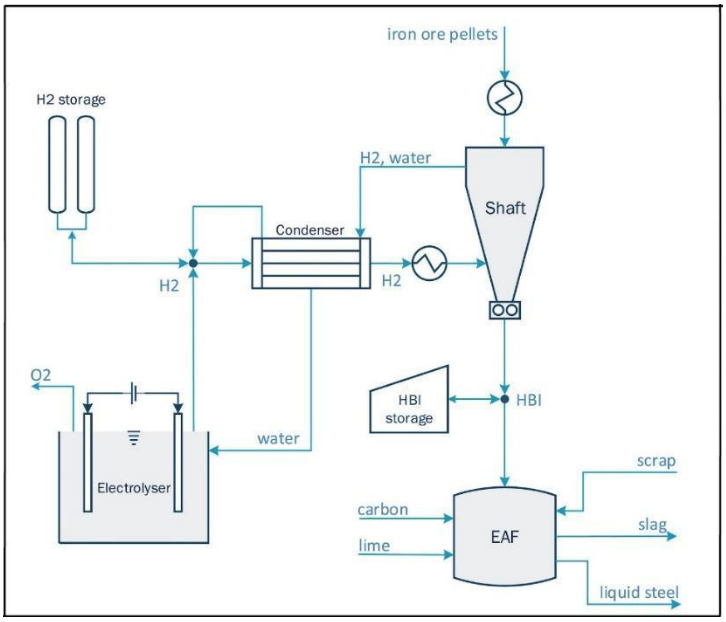


Figure 26: Hydrogen direct reduction (H-DR) process for steel manufacturing (Vogl, Åhman, and Nilsson 2018).

The most successful example of H-DR technology is **HYBRIT**, a company based in Luleå, Sweden. Initiated in 2016 by three Swedish companies - SAAB, Vattenfall AB, and LKAB - the project investigated the possibility of producing iron sponges using hydrogen from fossil-free electrolysis, reaching feasibility in 2017. The main differences between the HYBRIT production process and the BF-BOF route include (1) the production of iron pellets without fossil fuels, (2) the use of hydrogen as a reduction agent obtained entirely from renewable energy-based electrolysis, and (3) the direct use of reduced iron in the EAF along with steel scrap. Shifting from the BF route to the H-DR route could reduce CO2 emissions from 1600kg/ton to 25kg/ton of crude steel (Pei et al. 2020). CO2 emissions from the DR process arise from the graphite electrodes used in hydrogen production and the carbon added to the EAF during the melting process.

Regarding the economic feasibility of the production process, it heavily relies on electricity prices and the availability of steel scrap. The electricity consumption for the DR process is 3488 kWh per metric ton of liquid steel, significantly higher than the 235 kWh required in the BF process. In 2018, a cost comparison between the two routes showed an increase of 20% to 30% in favour of the BF route (Pei et al. 2020).

4.1.2 3D printing in cement production

Cement-based construction 3D printing (C3DP) is considered one of the most prominent technologies for decreasing the building's carbon footprint. Most of the existing cement 3D printing techniques use the extrusion method, namely the pouring of the cementitious mixture through a robotic arm controlled by a software. The main advantage of this technique is the possibility of building complex structures on site, even in harsh conditions, with reduced consumption of labour and natural resources (Gangotra, Del Gado, and Lewis 2023). To work properly, the technology needs cementitious mixtures with specific properties, such as (1) printability, (2) buildability and (3) pump-ability (Cao et al. 2022). Furthermore, to reduce the emissions of the extrudable material production process, supplementary cementitious materials (SCMs) are needed. SCMs are usually composed of industrial wastes, clay, recycled concrete and alternative binders (Gangotra, Del Gado, and Lewis 2023). Another way to reduce emissions is through the building design. Thanks to the digitalization of the process, building design can be optimised to reduce the consumption of resources and reduce waste. A downside of this technology is that while the emissions related to the printing process are lower compared to the traditional building process (if the electricity used by the printing process comes from renewable sources), the emissions related to the production of cementitious mixtures are comparable to the traditional Portland cement. In fact, printable mixtures could contain higher levels of Portland cement with respect to traditional cement if very high strength constraints are needed for a specific project. Printable concrete mixtures have a carbon footprint of around 230-295 kg CO2/m3 while the mixtures with higher concentrations of Portland cement reach 330-680 kg CO2/m3 (Gangotra, Del Gado, and Lewis 2023).

WASP (World’s Advanced Saving Project) is an Italian company that operates in the concrete 3D printing sector. The company was founded in 2012, and it produces and uses its own 3D printing machines. The process in concrete printing consists in building walls layer by layer, both onsite or offsite and then transporting them to be assembled (Figure 27). The printers can operate in a temperature range that varies between 10°C to 40°C (Bello and Memari 2023). The mixture used by WASP 3D printers are made of easy to find natural materials, such as soil, straw chopped rice, rice husk and hydraulic lime. Moreover, WASP buildings follow a cob design that provides all the strength necessary to the building without the need to add steel.

Figure 27: The 3d printed house Gaia by WASP[48]

4.1.3 Digital twins in chemical manufacturing

A digital twin (DT) is a technology that enhances the efficiency of complex production processes by providing insights into energy consumption, workforce optimization, resource utilisation, and time management (Figure 28). The increase in efficiency is possible through the replica of physical objects and processes in a virtual environment, allowing to break down the critical events occurring during the production processes (Javaid, Haleem, and Suman 2023). The first theorization of DT was in 2002 when Micheal Grieves, from the University of Michigan, proposed the concept of a model with three components: virtual space, real space, and a data flow link between the two spaces (Singh et al. 2021). Subsequently, DT has been implemented in infinitely numerous and heterogeneous processes since it can be used in every production facility with a minimum level of automation.

The main characteristics and abilities of DT are (1) cost-effectiveness, (2) waste reduction, (3) safety compared to the physical object replicated, (4) optimised solutions and improved maintenance (Singh et al. 2021).

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[48] https://www.3dwasp.com/en/3d-printed-house-gaia/

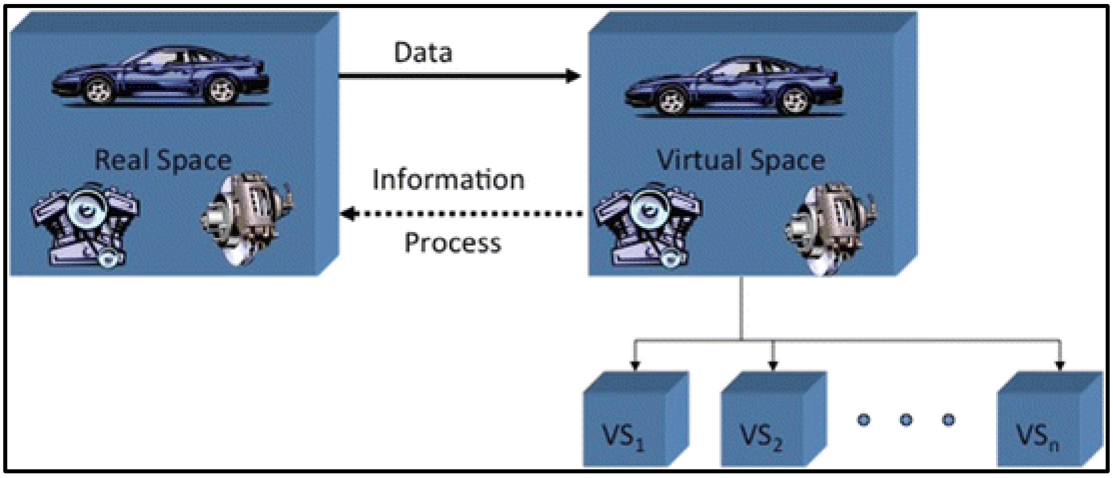

Figure 28: Schematic concept of digital twins (Grieves and Vickers 2017)

DT is cost-effective since it allows the prototyping of products or processes without the use of physical material and performing destruction tests in a virtual environment. Considering the inflation, the cost-effectiveness of DT should improve in the future since the cost of virtual testing is constant over time. Furthermore, another effect connected to the virtual prototyping process is waste reduction. Testing a product in a virtual environment allows for a reduction in the material consumed, releasing the final product without producing any waste. DT could improve the safety conditions in activities such as mining, and oil and gas extraction, offering the possibility of accessing the process remotely. Moreover, thanks to its prediction ability, DT can reduce the risk of accidents. Finally, DT could transform the maintenance activities from heuristic and worst-case scenarios approaches to the prediction of damages through simulation, allowing the scheduling of the maintenance in advance. However, DT also has to face challenges in the near future. Since DT influences all the phases of the production process, organisational siloing, or the miscommunication of information between different organisational areas (e.g., design, engineering, production, and support), represents a potential barrier to the technology implementation (Grieves and Vickers 2017). Another important obstacle is our understanding of the physical world. To work properly, DT requires us to be able to model and simulate real events and their effects on materials.

ReciChain is a programme developed by BASF, a German company based in Ludwigshafen. ReciChain adopts physical tracers, digital twins and blockchain to track the lifecycle of plastic materials. These tracers are embedded into plastics, allowing for the monitoring of their journey through the value chain. This digital representation enables precise tracking and management of plastic use, disposal, and recycling processes. The reciChain platform has shown promising results in improving the recycling rates and sustainability of plastics. By providing a clear digital trail for plastic materials, BASF aims to incentivize recycling and enable a circular economy for plastics. This approach not only helps reduce environmental impact but also adds value for agents across the plastics supply chain by ensuring material traceability and authenticity. The introduction of digital twins in this context allows for real-time data analysis and decision-making, optimising the recycling process and supporting sustainability goals.

4.1.4 Agrivoltaics in agriculture

Rem Tech Srl is an Italian company based in Asola, Italy that holds the patent for Agrovoltaico®. This technology consists of a bi-axial system, positioned at 5 metres above the ground level, enabling the maximisation of electricity production while leaving the ground free for agricultural use. The presence of bifacial photovoltaic modules also allows for increased electricity generation. REM TEC has also patented a fixed system that enables the cultivation of various agricultural species while allowing passage for all agricultural machinery. This type of installation readily adapts to different types of terrain, capable of withstanding slopes of up to 15%. Agrovoltaico seems to have the same environmental performances as ground-mounted systems. The same occurs for the economic results, due to the higher productivity of the sunlight tracking system and the decrease in material use necessary for the tensile structure of the plant (Amaducci, Yin, and Colauzzi 2018).

4.2 Regional case studies

4.2.1 Barcelona Mobility Plan and Initiatives

Barcelona is actively leading the transition towards sustainable urban mobility within the European Union. Recently, the city has updated its Urban Mobility Plan 2024 with the goal of achieving 80% modal split favouring sustainable transportation modes by 2024 (Urbana and Infraestructures 2022). This plan focuses on ensuring universal access within the city by promoting healthy and sustainable modes of transport such as walking, public transport, cycling, and other personal mobility vehicles. It encompasses five key areas: safe mobility, sustainable mobility, healthy mobility, equal mobility, and smart mobility, outlined through 62 lines of action incorporating over 300 measures.

The recent update of the plan incorporated 84% of the suggestions received during the revision process. The main enhancements include:

- **Walking:** Accelerating the reduction of accidents, incorporating a gender perspective into walking initiatives, and enhancing traffic light signalling.
- **Public transport:** Strengthening cooperation with other administrations to improve intermunicipal public transport services and complementary routes, and setting new accessibility goals for public transport stops.
- **Cycling and other personal mobility vehicles:** Enhancing traffic light signalling for cyclists, improving connectivity between the city's cycling network and the regional network, upgrading bicycle parking safety, and expanding shared mobility services to the metropolitan level.
- **Motorised private vehicles:** Expanding the low emission zone and exploring complementary measures, fully implementing 30km/h speed limits citywide, and integrating the plan's measures with the city's parking strategy to encourage public transport use.

Urban mobility is more than the sum of the set of journeys made by people and goods in the urban area, in many possible modes, with the purpose of carrying out their daily activities. Today, mobility constitutes a social right of citizens including values such as social cohesion and inclusion, health and safety, especially in relation to the most vulnerable groups, equity, sustainability and participation in a model that develops around different people’s needs. In addition to being a right, urban mobility is the backbone of the social, economic and cultural model of cities.

The PMU 2024 (Pla de mobilitat urbana de Barcelona) focuses on a strategic approach to urban planning within a metropolitan context, despite its primary measures and actions being limited to a 100 km² area within Barcelona. It recognizes that addressing issues such as transportation infrastructure, mobility, congestion, and environmental concerns requires a broader perspective that encompasses the entire Barcelona metropolitan area and region. The plan aligns with the objectives of the Metropolitan Mobility Plan and the 2021-2030 Infrastructure Master Plan, emphasising sustainable and equitable access to mobility for all citizens. The goal is to shift modal distribution towards environmentally friendly modes of transportation, thereby fulfilling local environmental quality standards and reducing pollution in line with European regulations.

The benefits resulting, directly or indirectly, from the implementation of the measures of the PMU 2024 accrue to society as a whole. These benefits are assessed across three dimensions of sustainability: economic improvement, environmental enhancement, and social progress. The impact of these improvements extends beyond the users of the transportation networks, affecting the entire population of the city collectively. Among the benefits outlined in the plan, savings in travel time and waiting periods have a significant economic impact. This is because time saved directly influences productivity and efficiency within the population, as time spent on commuting is typically considered unproductive. Therefore, quantifying these time savings in economic terms will be utilised to calculate the economic benefits of implementing the new network.

Figure 29 shows the Low Emissions Zone in the Barcelona metropolitan area, implemented since December 1, 2017. The area addresses environmental air pollution episodes by aiming to reduce nitrogen dioxide and particulate matter emissions. The goal is to decrease traffic by 10% in the next five years and by 30% within 15 years to meet WHO recommendations. During episodes of high air pollution, vehicles without emission labels are prohibited from circulating within the Low Emissions Zone, affecting vans registered before 1994 and cars registered before 1997. These restrictions are expected to reduce urban emissions of NO2 and PM10 by 18%. To mitigate the impact on private transport, special measures enhancing public transportation are implemented, including increased service during pollution episodes, guidance to park-and-ride stations, introduction of a discounted T-aire ticket for public transit during episodes, and provision of a T-verda card offering three years of free public transport to vehicle owners who dismantle their vehicles without acquiring new ones.

Figure 29: Barcelona's low emission zone in green

4.2.2 Taranto steel plant

ITALSIDER is a historic company in the Italian steel industry. The history of the Taranto steel mill is marked by significant milestones spanning several decades. It began with the laying of the first stone on July 9, 1960, followed by the launch of Tubificio in 1961 and the activation of the first blast furnace on October 24, 1964. The plant was officially inaugurated on April 10, 1965, by President Giuseppe Saragat, operating under state ownership as Italsider. In 1989, Ilva spa was established, consolidating Finsider and Nuova Italsider. The year 1995 marked a pivotal moment with the privatization of the large steelworks in Taranto, transferring ownership to the Riva Group, under the name ILVA acciaieria di Taranto[49]. Legal challenges emerged in 2012 when precautionary custody orders were signed by Judge Patrizia Todisco as part of the "Ambiente Svenduto" investigation, leading to the seizure of certain plant areas. Despite subsequent governmental approvals and management changes, including the appointment of Enrico Bondi as commissioner and Edo Ronchi as deputy commissioner, legal battles ensued. In 2020, an agreement was reached between Ilva commissioners and ArcelorMittal to negotiate a new governance agreement. The year 2021 saw Invitalia's entry into the share capital of AM InvestCo Italy, resulting in the renaming of the group to Acciaierie d'Italia. However, by 2023, efforts to reach agreements on recapitalization or plant acquisition between ArcelorMittal and Invitalia failed, leading to uncertainties. In 2024, tensions escalated between the public partner and stakeholders, with issues such as supply chain payments coming to the forefront. Invitalia faced controlled administration, prompting the government to seek new investors[50].

- **Environmental Concerns**

ILVA Taranto is an industrial facility located near the Tamburi district of Taranto, spanning approximately 15 Km^2 (Figure 30). The Tamburi district is home to about 18,000 residents, who have been directly affected by the polluting dust, including asbestos, known for its high carcinogenicity as stated in the latest IARC monograph. Two expert reports filed in 2012, one chemical and one epidemiological, demonstrate pollution in Taranto and its impact on public health. Various charges have been brought against Emilio Riva, Nicola Riva, the plant director, and the Responsible Party, including manslaughter and intentional disaster, poisoning of food substances, and violation of workplace precautions. In addition to this, it is reported that 70 hectares of mineral parks have been contaminated by the dust[51].

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[49] https://archiviostorico.fondazionefiera.it/entita/884-italsider-ilva

[50] https://www.ansa.it/sito/notizie/economia/aziende/2024/02/19/la-storia-dellilva-dallitalsider-a-arcelormittal_0caf06da-7009-4a5f-9acc-9119d85b07ff.html

[51] https://ilgiornaledellambiente.it/ilva-di-taranto-disastro-ambientale/

Figure 30: Taranto steel plant’s location

Residents of the Tamburi district in Taranto, located close to the former Ilva mining parks, have long endured dust carried by the wind, coating everything in a reddish hue. Investigations led to the covering of the mining parks with two huge sheds between 2018 and 2020, spanning 250,000 square meters in total.

The former Ilva remains operational as Italy's sole national strategic industrial facility, renowned for its remarkable output and integrated manufacturing process spanning from coal and iron to steel. Employing around 10,000 workers until 2017, it emerged as the fourth-largest steel center in Italy, featuring five blast furnaces towering over 40 meters high. Taranto was selected for its proximity to the port, streamlining material transportation. Despite breaching a 1934 royal decree prohibiting industrial establishments near residential zones, it was viewed as a pivotal investment for fostering economic growth in Southern Italy, aiming to supplant steel imports with domestic production. The Riva family, who owned the plant from 1995 to 2012, was found by the Taranto Court of Assizes to have inflicted irreversible damage on the city's health. They, along with 26 other individuals including executives, managers, and politicians, were initially convicted of criminal conspiracy resulting in environmental catastrophe, food contamination, and deliberate neglect of workplace safety measures. Despite this verdict, as reported by Ansa in January 2023, some have lodged appeals against the judgment.

- **hydrogen valley hubs**

The process of reducing carbon emissions in the Italian steel industry will require a shift from traditional blast furnaces to electric furnaces fuelled by Direct Reduced Iron (DRI), produced using hydrogen. However, this transition alone won't suffice; there's also a need to modernize ancillary operations like logistics. To address this, Acciaierie d'Italia has partnered with Avantgarde, a leading Puglian firm in railway locomotive technology, to convert diesel-powered locomotives to hydrogen or hybrid systems for internal rail logistics at their facilities in Taranto, Genoa, and Novi Ligure. This initiative is part of Acciaierie d'Italia's plan to decarbonize the Taranto steel plant by transitioning to green hydrogen energy[52].

Green hydrogen is set to revolutionize Italy's steel industry by fuelling the production of direct reduced iron (DRI), thereby facilitating decarbonization efforts. The European Commission has earmarked EUR 402 million to establish a green hydrogen hub in Puglia, as reported by Reuters, aiming to utilize renewable energy sources for hydrogen production and replace fossil fuels in energy-intensive sectors across the EU. The Green Valley project, located near Brindisi and Taranto, will boast 260 MW of solar power generation and 160 MW of electrolysis capacity for hydrogen production. This hydrogen will be utilized in DRI production to decarbonize steelmaking processes at Italy's largest steel plant in Taranto (ADI) and other consortium steel mills. Italian steelmakers faced a 2.5% reduction in steel production in 2023 compared to 2022 due to global demand fluctuations and high energy costs. To support industries like steel, paper, and glass in their decarbonization efforts, the European Commission approved a EUR 550 million Italian scheme. This funding, available until the end of 2025, will facilitate the transition from fossil fuels to green hydrogen in industrial processes[53].

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[52] https://hydronews.it/acciaierie-ditalia-convertira-a-idrogeno-la-rete-ferroviaria-interna-agli-stabilimenti-con-laiuto-di-avantgarde/

[53] https://gmk.center/en/news/eu-has-allocated-e402-million-to-create-a-green-hydrogen-hub-in-italy/

5 Labor market implications of decarbonization

Country analysis of the manufacturing industries in 6 selected countries (Austria, Germany, Italy, the Netherlands, Poland, and Spain), reveals the vulnerability of certain regions in each country to decarbonization and energy transition (Table 4). Specifically, we can identify regions with more than 10% of their manufacturing workforce employed in one of the three subsectors of Steel manufacturing, Cement production, or Chemical manufacturing.

In the ***steel manufacturing*** sector, Germany (Dusseldorf), Italy (Valle d’Aosta) and Spain (Principado de Asturias) each have one vulnerable region. Among all regions in these 6 countries, the highest share of employment in steel manufacturing belongs to **Valle d’Aosta** in Italy with more than **27%** of the manufacturing workforce.

In the ***cement production*** sector, Poland has one vulnerable region (Świętokrzyskie) while Spain has two (Ciudad de Melilla, and Comunitat Valenciana). Among all regions in these 6 countries, the highest share of employment in cement production belongs to **Świętokrzyskie** in Poland with more than **16%** of the manufacturing workforce.

In the ***chemical manufacturing*** sector, all top three regions in Germany (Darmstadt, Dusseldorf, and Koln) as well as the Netherlands (Zeeland, Limburg, and Groningen) are highly vulnerable in terms of employment. Among all regions in these 6 countries, the highest share of employment in chemical manufacturing belongs to **Zeeland** in the Netherlands with more than **18%** of the manufacturing workforce.

Table 4: Most vulnerable regions to decarbonization with high (>10%) share of labour in manufacturing

	Steel manufacturing	Cement production	Chemical manufacturing
Austria	-	-	-
Germany	Dusseldorf (14.20%)	-	Darmstadt (16.00%), Dusseldorf (13.90%), Koln (11.90%)
Italy	**Valle d'Aosta (27.30%)**	-	
Netherlands	-	-	**Zeeland (18.20%)**, Limburg (10.90%), Groningen (10.30%)
Poland	-	**Świętokrzyskie (16.50%)**	-
Spain	Principado de Asturias (19.30%)	Ciudad de Melilla (13.20%), Comunitat Valenciana (10.70%)	-

5.1 Digitalization and decarbonization

The EU's commitment to decarbonization, as part of its broader climate change mitigation strategy, has significant implications for employment across member states. The transition towards a low-carbon economy is expected to have a dual effect on the job market, creating new opportunities while also necessitating the phasing out of certain industries.

The decarbonization of energy-intensive industries is a focal point of concern, especially considering the uncertain future of nearly 3 million European jobs. These industries provide direct employment to around 2.6 million people and are integral to critical and strategic value chains within the EU economy[54]. The renewable energy sector, in particular, has seen a fluctuating trend in employment within the EU. Despite an increasing share of renewable energy, job growth in this sector has experienced a decline, followed by stagnation. Factors contributing to this include the aftermath of the financial crisis, the relocation of manufacturing capacities outside Europe, and changes in subsidy schemes within the EU[55].

The advent of digital technologies such as Artificial Intelligence (AI) on the other hand, is a pivotal force shaping the future of work in the EU. Digitalization spurs job creation through three primary mechanisms. Initially, investments in digital infrastructure and machinery catalyse employment in related manufacturing sectors. Subsequently, cost reductions from digitalization and automation, transferred to consumers, stimulate demand and further job opportunities. Moreover, novel digital-based products introduce new markets, albeit with the potential to displace existing ones.

Nevertheless, to attain the environmental, economic, and social goals associated with decarbonization and outlined in the European Green Deal including emission reduction, enhancement of industrial competitiveness, and job growth, it is essential to foster the growth of production chains at the national level. This includes the advancement of key drivers such as research and development, infrastructure, and the transformation of both direct and indirect labour forces to align with the emerging industrial and technological paradigm (Rugiero 2022).

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[54] https://www.etui.org/decarbonizing-energy-intensive-industries-what-are-risks-and-opportunities-jobs

[55] https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/employment-energy-sector-2020-07-09_en

5.2 Regional examples

Here we present three examples of decarbonization efforts in Italy and their broader impact on labour market and employment. Through these examples, we highlight the role businesses associations and local authorities to work together and create solutions to address these issues (Rugiero 2022).

5.2.1 Steel manufacturing

The Taranto steel plant, Europe's largest integrated steel facility, has been under scrutiny due to its large negative environmental impacts. Despite its strategic importance to national production, its current operations are deemed unsustainable. In 2020, amidst restructuring efforts, the plant produced 3.5 million tons of steel with over 8,000 direct workers, generating 8.3 million tons of CO2 emissions. More than half of the workforce are employed in the smelting process in the plant.

In order to reduce emissions and decarbonize its operation, the company has developed a 3-step plan aimed to transition to hydrogen-based processes within a decade and ensure full employment within three years. In the first step, a quarter of the production will be performed in a more sustainable fashion. In the second stage the production process will be transitioned to DRI and EAF. In the final step, the operation will transition to hydrogen. As a result, the company will be able to meet the 2050 climate objectives in a progressive manner. The cost of such transition in ten years is estimated to be around EUR 4.7 billion euros and a sharp decrease in employment levels will be expected. If the company keeps its current level of production while transitioning to EAF and DRI, it probably will require only about 1,000 – 1,500 workers in the smelting process and between 2,000 and 3,200 workers for the whole operations. This highlights the vulnerability of steel manufacturing to decarbonization efforts and the need for greater social programs for re-training and re-employment of current workforce.

5.2.2 Cement production

The cement production sector in Italy, employing approximately 6,000 workers directly in cement plants, faces significant challenges. Despite contributing to 5% of total CO2 emissions, the sector exhibits a disproportionately high emission rate relative to its economic output. Over the past 16 years, the sector has witnessed major downsizing, with national consumption dropping from 46 million tons in 2005 to 18 million tons, resulting in a 60% market loss. The sector's workforce is characterised by a higher-than-average age of employees while significant turnover in the coming years is expected. The association of Italian concrete businesses, Federbeton, has developed a strategy for the decarbonization efforts in the sector as they present a critical challenge for the sector's survival, considering its difficult recovery from years of crisis. It has also highlighted enormous challenges that the sector is facing such as the lack of public aid and a growing competition from foreign operators. Nevertheless, it shows some decarbonization potential within the industry such as the development of renewable energy in the exhausted quarries. It also calls for the establishment of a "joint coordination group" combined of private sector representatives and public authorities to facilitate the decarbonization process[56].

5.2.3 Chemical manufacturing

Eni's proposal for blue hydrogen production in Ravenna, alongside its efforts to repurpose the Porto Torres petrochemical site in Sardinia for green chemistry production, signifies a concerted effort towards energy transition and decarbonization in the chemical manufacturing sector. Furthermore, Eni and other major chemical manufacturers in Italy have developed a special protocol which aims at an 80% cut in GHG emissions relating to the life cycle of their chemical products by 2050[57]. These initiatives prioritise a participatory industrial relations system, emphasising transparent communication and active involvement of workers. Measures include establishing information and consultation systems, periodic sessions, and joint committees to discuss corporate strategies related to engineering, environmental protection, research, innovation, circular economy, and renewables. The protocol encompasses various workforce-related aspects such as the Generational Pact to encourage turnover, utilisation of expansion contracts legislation, digitization, training, new work organisation methods, and welfare enhancement. This approach serves as a model for industrial relations, particularly in the upcoming renewal of national contracts in the energy sector, fostering a culture of collaboration and inclusivity.

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[56] https://www.federbeton.it/Portals/0/pubdoc/pubblicazioni/Rapporti/La_strategia_di_decarbonizzazione_del_settore_del_cemento_slide.pdf?ver=2021-10-18-100323-973

[57] https://www.eni.com/it-IT/media/news/2020/12/eni-organizzazioni-sindacali.html

6 Conclusions

In this report we focused on 3 key economic sectors in terms of GHG emissions which include manufacturing, agriculture, and transportation[58]. For each economic sector, we evaluated emerging technologies and their GHG potential as well as their economic performance.

Our analysis reveals important dimensions of the landscape of decarbonization technology development and deployment:

1- There is no one-size-fit-all. Decarbonization technologies are diverse in scale and ambition, ranging from those with net-negative emission such as CDR and BECCS to those with moderate emission reduction ambitions such as agrivoltaics.
2- Cross-cutting technologies such as carbon capture and storage are well positioned to be adapted by multiple sectors and processes concurrently, leading to faster cost reduction to greater adoption rate.
3- Digital technologies such as emerging generative AI methods are changing the landscape of many businesses and industries, opening up new opportunities for decarbonization through increasing efficiency and reducing waste, but also threatening the labour market structures by creating unfair conditions for the traditional workforce which may result in dismissal or redundancy.
4- Decarbonization measures are usually more investment intensive than their traditional competitive measures. This is mainly due to the nature of any innovation and breakthrough which requires a large amount of financial support for scaling up at the commercial and competitive level.
5- Decarbonization efforts in local businesses are often the result of uncoordinated and singular stances of innovative solutions initiated by socially and environmentally conscious business owners and technology developers, rather than coordinated efforts by the whole industry to move away from fossil fuel energy and emission intensive processes. This highlights the unique role of business associations in incentivizing innovation among their members and facilitating the dissemination of sustainability ideas through their professional network.
6- Finally, we should emphasize that decarbonization methods should be deployed in coordination with other support measures to ensure a just and equitable transition to a greener economy. Otherwise, the likely negative impact of decarbonization measures on employment can hinder their broader adoption and acceptance by the business community and end-users.

The results of this report will provide a base for identifying the best business practices across the EU in Task 7.4. They will also serve as an integral part of the Net Zero Business Consultant tool developed in task 8.3.

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[58] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Quarterly_greenhouse_gas_emissions_in_the_EU

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8 Annex

8.1 Decarbonisation of steel manufacturing in the EU

8.1.1 Austria

Background
The EU steel market is facing challenges such as rising production costs and increased imports of cheaper steel. As a result, steel companies are forced to shut down or reduce capacity for maintenance to balance supply and demand. Austria, home to five steel plants, including two blast furnace plants (BF BOF) – Donawitz and Linz – and three electric arc plants (EAF) – Graz, Kapfenberg, and Mitterdorf, is also experiencing a reduction in steel production. In 2022, steelmakers in Austria decreased production by 4.7% compared to 2021, amounting to 7.51 million tons. In December 2022, 560 thousand tons of steel were produced, marking a 13.8% annual decrease but a 0.5% monthly increase.
Top regions (employment share in all manufacturing)[59]
• Steiermark (9.3%) • Sud Osterreich (7.8%) • Niederosterreich (7.6%)
Example
Both the production and utilization of steel belts contribute to the emission of CO2. In 2022, a system developed to gather, evaluate, and analyse data related to the carbon footprint. This will aid in deriving and implementing suitable actions. Berndorf AG and the management of the Berndorf Band Group have initiated an extensive project with the goal of achieving carbon neutrality for the Berndorf site by 2040. As of October 2022, the "Climate Neutrality by 2040" project was launched, expanding the previous focus on the "carbon footprint" to the broader objective of achieving climate neutrality. The photovoltaic system's second expansion phase will include equipping Obj. 97 with photovoltaic panels, requiring roof construction reinforcement. Following a detailed structural assessment, roof areas suitable for a photovoltaic system were identified. Installation work commenced in the eastern area of the new building section in autumn 2022. The system is anticipated to become operational in spring 2023, generating 325 kWp of output. Berndorf AG and the management of the Berndorf Band Group are committed to achieving Carbon Neutrality for the Berndorf site by 2040. The "Greenhouse Gas Protocol" (GHG Protocol) will serve as a guideline for addressing various sources of CO2 and greenhouse gas emissions [60].

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[59] https://doi.org/10.2908/SBS_R_NUTS06_R2

[60] https://www.berndorfband-group.com/wp-content/uploads/2022/08/Berndorf-Band-Environmental-Statement-2022.pdf

8.1.2 Germany

Background
The German steel industry is a major emitter of greenhouse gases, releasing approximately 67 million tonnes of CO2 equivalent annually. Key players like Thyssenkrupp contribute significantly to this total, with the company responsible for 2.5% of Germany's total CO2 emissions. In response to this environmental challenge, the German government has announced plans to invest USD 6 billion in steel research and technology, particularly focusing on hydrogen production, as part of efforts to reduce emissions from the steel industry.
Top regions (employment share in all manufacturing)[61]
• Dusseldorf (14.2%) • Gieben (9.0%) • Nordrhein - Westfalen (8.5%)
Example
The EU Commission has approved state aid for the German "tkH2Steel" decarbonization project with a total funding of approximately two billion euros. The funding will be provided through "Initial Grant" and "Conditional Payment" mechanisms, supporting innovative plant technology and the reduction of natural gas use. The project aims to quickly reduce CO2 emissions through an ambitious hydrogen ramp-up, positioning it as a driver of the European hydrogen economy and a catalyst for cross-border hydrogen infrastructure development. ThyssenKrupp's own investment is nearly one billion euros. The project involves a new plant combination in Europe's largest iron and steel plant, featuring a 100% hydrogen-capable direct reduction plant with a production capacity of 2.5 million metric tons of directly reduced iron annually. This innovative concept will significantly contribute to industrial climate change mitigation by saving up to 3.5 million metric tons of CO2 per year, with the plant planned to start operations by 2029[62].

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[61] https://doi.org/10.2908/SBS_R_NUTS06_R2

[62] https://www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/eu-commission-approves-german-federal-and-state-government-fund-ing-for-thyssenkrupp-steels-tkh2steel-decarbonization-project-228875

8.1.3 Italy

Background
Italy is a significant player in the European steel industry, ranking as the EU's second-largest steel producer. In 2021, the country had nearly 30,600 people employed in the steel sector and produced 24.4 million tons of steel. However, in 2022, due to factors like high production costs, weak demand, and low cash flow, steelmakers reduced production and halted some activities. Despite these challenges, there is optimism that the Italian steel sector may experience growth in the coming years, suggesting its potential to overcome obstacles and achieve new goals[63].
Top regions (employment share in all manufacturing)[64]
• Valle d'Aosta (27.3%) • Puglia (7.4%) • Umbria (5.9%)
Example
Maintaining primary steel production while decarbonizing is crucial for Italy's economic development. Italy is a major European steel producer, with 82% being recycled steel and 18% being primary steel produced in Taranto's Acciaierie d'Italia plant. The Taranto plant emitted 8.3 Mt of CO2 and other pollutants in 2020. The upcoming industrial plan for Taranto offers a unique opportunity for a green steel project, with Direct Reduced Iron (DRI) technology being the preferred choice for decarbonization. Converting the plant to gas-fired DRI would require a 2.5 billion euro investment, leading to environmental benefits without compromising product quality. Eventually, green hydrogen could replace natural gas, though current hydrogen technologies are expensive. Public investment in DRI is crucial, aligned with long-term national climate goals. While DRI might reduce labour requirements, alternative employment opportunities in green hydrogen, renewable energy, and steel finishing could offset this[65].

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[63] https://gmk.center/en/interview/siderweb-in-2023-steel-demand-in-italy-is-expected-to-decrease-but-production-should-grow

[64] https://doi.org/10.2908/SBS_R_NUTS06_R2

[65] https://eccoclimate.org/taranto-primary-steel-production-in-the-decarbonization-challenge/

8.1.4 The Netherlands

Background

The Dutch steel and metals sector, while constituting only about 1% of the country's GDP, holds significant importance as a key supplier for construction, automotive, and machinery industries. The industry's performance is closely tied to the domestic construction sector, with many businesses oriented towards exports.

Despite ongoing strong demand and filled order books, Dutch businesses are increasingly cautious about investments due to geopolitical uncertainty, supply chain disruptions, and higher interest rates. Concerns over prolonged conflicts and energy market disruptions could potentially lead to a contraction of about 2% in metals and steel sales. In terms of output, metals and steel producers faced pressure on profit margins in 2022 due to soaring energy prices, which were challenging to fully pass on to customers. Some companies have begun to reduce capacity or explore alternative energy solutions to lessen dependence on natural gas.

Top regions (employment share in all manufacturing)[66]

- Groningen (5.1%)
- West Nederland (4.6%)
- Limburg (4.1%)

Example

Tata Steel in Ijmuiden, the largest steel producer in the Netherlands, emits 12.31 million tonnes of CO2eq per year through coal-based production. Decarbonizing this plant is vital to prevent carbon leakage and protect workers. Direct Reduction of Iron (DRI) is a process that uses hydrogen to replace coking coal in steel production, potentially reducing emissions to nearly zero. While converting blast furnaces to hydrogen DRI is challenging, transitioning from natural gas to hydrogen is possible. This shift has both advantages, such as converting existing fossil gas plants to hydrogen, and disadvantages, as projects using unabated natural gas could be seen as sustainable due to being "hydrogen-ready." This project would require a significant expansion of renewable capacity for hydrogen and electricity production. To produce 6.62 million tonnes of steel using renewable hydrogen and electricity, 21.2 TWh of renewable electricity would be necessary which exceeds the total wind production in the Netherlands for the year 2020. For reference, the Gemini wind farm, one of the largest in the Netherlands, generates 2.6 TWh of electricity annually with a capacity of 600 MW. To generate the required green hydrogen for decarbonizing Dutch steel production, approximately eight wind farms of the scale of Gemini would be needed. Converting the same plant to blue hydrogen would require an energy input of 1.3 Mt of natural gas and 1.4 TWh of renewable electricity. Emissions from this process depend on methane leakage upstream and CO2 capture rate during hydrogen production. While blue hydrogen requires only 7% of the electricity of green hydrogen, achieving low emissions hinges on high CO2 capture and low methane leakage rates. Assuming a 90% capture rate and above-mentioned leakage, emissions would be around 0.37 Mt of CO2eq.[67].

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[66] https://doi.org/10.2908/SBS_R_NUTS06_R2

[67] https://www.yara.com/corporate-releases/orsted-and-yara-seek-to-develop-groundbreaking-green-ammonia-project-in-the-netherlands/

8.3.5 Poland

Background
In 2022, Poland decreased its steel production by 8.6% compared to 2021, reaching 7.73 million tons, positioning the country as the 22nd largest steel producer globally, according to WorldSteel rankings. Across the European Union, steel production declined significantly in May 2023, dropping by 11.2% compared to the same period of the previous year, totalling 11.6 million tons. Moreover, from January to May 2023, EU steel production amounted to 56 million tons, reflecting a decrease of 10.4% year-on-year.
Top regions (employment share in all manufacturing)[68]
• Slaskie (5.9%) • Makroregion Południowy (5.8%) • Małopolskie (5.5%)
Example
The core of heavy industry in Southern Poland centres around the Upper Silesian coal basin, the last EU region with coking coal mining, essential for conventional primary steel production. Climate neutrality here may require Carbon Capture and Storage (CCS) due to challenges in converting to hydrogen-based DRI. The "New Processes" scenario suggests other technologies, yet allows some CCS integration by 2050. In the steel sector, CCS could be predominantly used in Poland, the Czech Republic, and Slovakia due to local coking coal resources and concerns about natural gas imports. Electricity demand for new applications totals 6 TWh in the region, with limited steam and hydrogen use. CO2 collection involves 5.8 Mt/a from various sources, including significant steel and cement plants, potentially reconsidering the initial "CCS-first assumption" due to stakeholder input, which could alter hydrogen needs and CO2 storage volumes[69].

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[68] https://doi.org/10.2908/SBS_R_NUTS06_R2

[69] https://wupperinst.org/fa/redaktion/downloads/projects/INFRA_NEEDS_d4-3.pdf

8.3.6 Spain

Background

In recent years, Spain has been ranked as the 16th largest steel producer globally, according to data from the World Steel Association. The country boasts several steel manufacturers and holds a significant position in both European and global steel markets. The automobile industry serves as the primary consumer market for Spain's steel sector, with substantial quantities of steel required for automobile manufacturing.

Top regions (employment share in all manufacturing)[70]

- Principado de Asturias (19.3%)
- Pais Vasco (9.3%)
- Cantabria (8.2%)

Example

ArcelorMittal has signed an MoU with the Spanish Government to invest EUR 1 billion in decarbonization technologies at its Asturias plant, aiming to reduce CO2 emissions by about 50% within five years. Additionally, the Sestao plant in Spain will become the world's first full-scale zero carbon-emissions steel plant. This transformation involves investing in a green hydrogen direct reduced iron (DRI) plant and a hybrid EAF at the Gijón plant. By 2025, the Sestao plant plans to produce 1.6 million tonnes of zero carbon-emissions steel by increasing circular recycled scrap, using green hydrogen-produced DRI, and powering all steelmaking assets with renewable electricity[71].

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[70] https://doi.org/10.2908/SBS_R_NUTS06_R2

[71] https://corporate.arcelormittal.com/media/case-studies/announcing-the-decarbonisation-of-our-spanish-operations-and-the-world-s-first-full-scale-zero-carbon-emissions-steel-plant

8.2 Decarbonisation of cement production in the EU

8.2.1 Austria

Background

In 2022, Austrian export of cement products reached USD 45.8 million, making it the 54th largest exporter of cement in the world. In the same year, cement was the 442nd most exported product in Austria. The main destination of cement exports from Austria are Slovenia, Germany, Hungary, Italy, and Czechia[72].

Top regions (employment share in all manufacturing)[73]

- Tirol (7.8%)
- Karnten (7.3%)
- Burgenland (5.6%)

Example

Lafarge Zementwerke, OMV, VERBUND, and Borealis have entered into a Memorandum of Understanding (MOU) with the shared goal of jointly planning and constructing a comprehensive plant by the year 2030. This plant will be designed to capture carbon dioxide (CO2) emissions and convert them into synthetic fuels, plastics, or other chemical products. The primary objective is to establish an integrated, cross-sector value chain that aims to achieve the capture of nearly 100% of the annual CO2 emissions, totaling approximately 700,000 tons, generated by Lafarge's cement facility in Mannersdorf, Austria.

The ultimate aim of this collaborative effort is to utilize the captured CO2 as a valuable resource. In conjunction with the production of green hydrogen derived from renewable energy sources, which will be facilitated by VERBUND, OMV will undertake the transformation of the captured CO2 into renewable-based hydrocarbons. These hydrocarbons can then be utilized for the production of renewable-based fuels or serve as a vital feedstock for Borealis in the creation of value-added plastics. This initiative represents a significant step towards reducing carbon emissions and fostering sustainability in the industrial sector[74].

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[72] https://oec.world/en/profile/bilateral-product/cement/reporter/aut

[73] https://doi.org/10.2908/SBS_R_NUTS06_R2

[74] https://www.holcim.com/who-we-are/our-stories/advancing-co2-capture-storage-austria

8.2.2 Germany

Background

The German cement industry has evolved significantly in recent decades, becoming highly sophisticated with automated material transfer processes, stringent quality control measures, and the development of specialized cements for custom applications. Research centers and computer models support ongoing innovation in the industry. Production processes have been altered to reduce costs and meet environmental regulations, with a focus on improving energy efficiency through the conversion to dry production and optimizing waste-heat utilization. The industry has also witnessed a substantial increase in kiln capacity over the years, from an average of 350t/day in the 1960s to 2400t/day in the 1970s. Currently, the largest cement plant in Germany is the Rüdersdorf Plant in Brandenburg, with a capacity of 2 million tons per year, operated by Cemex OstZement GmbH[75].

Top regions (employment share in all manufacturing)[76]

- Oberfranken (7.8%)
- Oberpfalz (7.1%)
- Leipzig (6.8%)

Example

Heidelberg Materials, located in Germany, is set to become the country's first fully decarbonized cement plant. The project has received backing from the EU Innovation Fund.

Heidelberg Materials has launched the GeZero carbon capture project, aiming to achieve full decarbonization of cement production at its Geseke plant in Germany's North Rhine-Westphalia. The project, supported by the EU Innovation Fund, will establish a comprehensive CCS (Carbon Capture and Storage) value chain solution for an inland location, targeting the capture of 700,000 tonnes of CO_2 annually starting from 2029.

The GeZero project stands out as a unique initiative for sites that are not near coastlines or waterways. It encompasses innovative transportation solutions to bridge the gap until pipeline infrastructure becomes available. By capturing emissions from biomass that substitutes fossil fuels, the Geseke plant will produce fully decarbonized cement and clinker, setting it apart as an early leader in deep industrial decarbonization.

The project involves constructing a new facility, including a 2nd generation oxyfuel kiln with CO_2 purification, a liquefaction unit, rail loading, and interim storage capabilities. Additionally, renewable energies, particularly from a new photovoltaic plant on the factory premises, will exclusively power the electrical energy demands of the project. Construction is expected to commence in 2026, with commissioning scheduled for 2029[77].

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[75] https://www.globalcement.com/magazine/articles/519-german-cement-focus

[76] https://doi.org/10.2908/SBS_R_NUTS06_R2

[77] https://www.heidelbergmaterials.com/en/pr-2023-07-13

8.2.3 Italy

Background
The cement market in Italy is experiencing rapid growth in terms of value and production. Turnover has risen by 1.8%, and the number of companies in Italy has increased by 1.2%. However, the number of employees in the sector has decreased due to the recent health crisis. Cement production is primarily concentrated in northern Italy, with a growth rate of 11.4% in recent years. Portland cement is the most produced type in Italy. One significant trend in this market is the focus on sustainability, as cement is seen as having a high environmental and energy cost. Ecological cement, made from recycled materials with CO_2 absorption capabilities, has been developed in response to the growing importance of environmentally sustainable solutions. Overall, the Italian cement market shows promise for growth, but it is important to consider environmental factors and work towards sustainable solutions[78].
Top regions (employment share in all manufacturing)[79]
• Sardegna (8.2%) • Calabria (8.1%) • Sicilia (7.3%)
Example
The CLEANKER project aims to enhance the integrated Calcium-looping process for CO_2 capture in cement plants. It seeks to achieve cleaner clinker production through this innovative technology.The CLEANKER project, funded by Horizon 2020, focuses on CO_2 capture from cement production. It centers on the calcium looping (CaL) technology, deemed one of the most promising methods for CO_2 capture in cement plants. The project's main objective involves designing, constructing, and operating a CaL demonstration system within Buzzi Unicem's cement plant in Vernasca, Italy. With a budget of EUR 9,237,851 the project received an EU contribution of EUR 8,972,201. It involves 13 partners, and it is coordinated by the Laboratory of Energy and Environment of Piacenza[80].

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[78] https://www.businesscoot.com/en/study/the-cement-market-italy

[79] https://doi.org/10.2908/SBS_R_NUTS06_R2

[80] http://www.cleanker.eu/

8.2.4 The Netherlands

Background

The Netherlands' cement industry benefits from its extensive coastal and inland waterways, enabling efficient transportation of imported materials by barge to inland locations. However, the prevalence of waterways presents challenges, influencing the types of cement needed due to the moist and sometimes salty environment. Consequently, blast furnace slag cement, offering enhanced durability, dominates the market. Despite limited domestic limestone resources, the Netherlands imports clinker and cement, primarily by sea and from neighboring countries like Germany and Belgium, as it has only one integrated cement plant with a capacity of 1.1 million tons per year. To meet the demand, the country imports 2-3 million tons of clinker annually[81].

Top regions (employment share in all manufacturing)[82]

- Limburg (7.3%)
- Groningen (5.3%)
- Utrecht (4.3%)

Example

The innovation trajectory of eco-cement in the Netherlands is scrutinized through an examination of the collaboration among eco-cement manufacturers, scientists, waste producers, and policymakers, within the broader context of market dynamics, policy frameworks, and societal factors, with a specific emphasis on standards and regulations. By analysing policy documents, media coverage, eco-cement utilization trends, and conducting interviews with relevant stakeholders, insights emerge into the multifaceted involvement of policymakers in shaping the development of eco-cement. This involvement spans various areas including building regulations, sectoral policies, waste management strategies, and science and innovation policies. Furthermore, the analysis reveals the intricate interplay between regulation and innovation in the cement industry, such as collaborative initiatives between waste authorities and cement producers to encourage waste reuse, and the absence of policies addressing CO2 emissions from cement production. Notably, the utilization of fly ash and sewage sludge as supplementary cementitious materials or fuels has emerged as a response to bans on their disposal. Despite a rising demand for green cement, challenges persist, with carbon policies demonstrating limited efficacy. These findings underscore the intertwined nature of eco-cement innovation and policy, showcasing mutual dependencies that drive progress within the sector (Kemp, Barteková, and Türkeli 2017).

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[81] https://cefic.org/a-pillar-of-the-european-economy/landscape-of-the-european-chemical-industry/netherlands/

[82] https://doi.org/10.2908/SBS_R_NUTS06_R2

8.2.5 Poland

Background

In the first half of 2022, Poland saw a notable surge in cement production, reaching 9.3 million tons, marking an 8.6% increase compared to the same period in 2021. Concurrently, national cement consumption rose by 11%, reaching 6.8 million tons, according to data from the Polish Association of Cement Manufacturers (SPC)[83].

Top regions (employment share in all manufacturing)[84]

- Świętokrzyskie (16.5%)
- Opolskie (6.5%)
- Lodzkie (6.4%)

Example

The Poland-EU CCS Interconnector project funded by Lafarge cement and other companies involves the establishment of a comprehensive system connecting industrial emitters in the vicinity of Gdansk, Poland, with available CO2 storage facilities in countries bordering the North Sea. This initiative encompasses an open-access, multi-modal liquid CO2 (LCO2) import-export terminal situated in the Port of Gdansk, complemented by a network of CO2 transport infrastructure. The objective is to facilitate the transportation of 2.7 million tons of CO2 annually during the 2025-2030 timeframe, with the capacity to transport up to 8.7 million tons of CO2 between 2030 and 2035.

Key components of the CCS interconnector project include:

- Multi-modal Liquid CO2 Export Terminal: Located in the Port of Gdansk, this terminal serves as a pivotal hub for importing and exporting LCO2 and for the exchange of CO2 between industrial sources and storage sites.
- CO2 Collector Backbone: Within the Port of Gdansk, a collector backbone infrastructure is established to efficiently connect nearby industries with the CO2 export terminal. This backbone ensures convenient access for industrial facilities in the vicinity of the port.
- Primary Export Infrastructure: Beyond the port area, primary export infrastructure is set up in the Gdansk hinterland. This infrastructure enables industries situated inland to access the CO2 export terminal via various transportation modes, including railcars, trucks, inland waterways, and potentially pipelines.

The project's overarching goal is to create a robust and flexible network that facilitates the movement of CO2 from industrial sources to storage locations, thereby contributing to carbon capture and storage efforts in Europe[85].

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[83] https://www.globalcement.com/news/item/14509-poland-s-cement-production-rises-by-8-6-in-first-half-of-2022

[84] https://doi.org/10.2908/SBS_R_NUTS06_R2

[85] https://ec.europa.eu/energy/maps/pci_fiches/PciFiche_12.9.pdf

8.2.6 Spain

Background

In 2022, cement consumption in Spain experienced a slight decrease of 1%, dropping to 14.9 million tons from 14.8 million tons in the previous year. Oficemen, the Spanish cement association, attributed this marginal decline to adverse weather conditions in December 2022. However, it highlighted that the consumption volume for the year was the second highest in the past decade. Despite a strong start to the year, sales began to taper off from May 2022 due to rising energy costs and inflation, exacerbated by factors such as the Russian invasion of Ukraine. Cement exports saw a notable decline of 16.8%, falling to 5.62 million tons from 6.75 million tons, while imports also decreased by 5.4% to 1.35 million tons from 1.43 million tons. Oficemen has linked the decline in exports to elevated domestic energy and CO2 emission costs dating back to 2019[86].

Top regions (employment share in all manufacturing)[87]

- Ciudad de Melilla (13.2%)
- Comunitat Valenciana (10.7%)
- Ciudad de Ceuta (7.4%)

Example

The Junta de Andalucía's Governing Council has approved the provision of accelerated start-up guidance for Spanish environmental cement projects. LafargeHolcim España's carbon capture plant in Carboneras (Almería) and Grupo Cementos Portland Valderrivas' waste recovery facilities in Alcalá de Guadaíra (Seville) are among the 10 projects selected for tailored guidance on necessary procedures. These projects collectively involve a EUR 400 million investment and the creation of 4,500 jobs.

The LafargeHolcim project, supported by Carboneras in Almería, focuses on CO2 circular economy initiatives, aiming to reduce environmental impact from clinker production by capturing 50,000 tons per annum of CO2 in its initial phase. This captured CO2 will be used for carbon fertilisation in greenhouses.

In Alcalá de Guadaíra, Seville, the project by Grupo Cementos Portland Valderrivas involves recovering non-hazardous waste to produce energy and decrease CO2 emissions. This initiative seeks to replace traditional fossil fuels like petcoke, previously used by the factory, while also renewing the factory's mining concession[88].

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[86] https://www.globalcement.com/news/item/15317-spanish-cement-consumption-falls-slightly-in-2022

[87] https://doi.org/10.2908/SBS_R_NUTS06_R2

[88] https://www.cemnet.com/News/story/172219/spanish-environmental-cement-projects-to-receive-accelerated-start-up-advice.html

8.3 Decarbonisation of chemical manufacturing in the EU

8.3.1 Austria

Background
The Austrian chemical industry experienced remarkable growth, with a production volume reaching 18.2 billion, surpassing the pre-crisis level by approximately 20%. It is important to note that a significant portion of this growth can be attributed to high prices. As of 2021, the chemical sector in Austria comprised 236 companies, providing employment to 47,700 individuals, indicating a slight increase of 1% in the workforce. Among these companies, only 56 have more than 250 employees. Chemical companies are dispersed throughout Austria, with key clusters located in Upper Austria near Linz and in the Vienna region. These clusters serve as important hubs for the industry's activities and contribute to its overall growth and development[89].
Top regions (employment share in all manufacturing)[90]
• Niederösterreich (4.3%) • Ost Osterreich (3.8%) • Oberosterreich (3.7%)
Example
Borealis and VERBUND have signed a ten-year power purchase agreement (PPA) to supply renewable hydropower to Borealis' operations in Schwechat, Austria, starting in January 2023. This agreement will provide approximately 220 gigawatt hours (GWh) of renewable electricity annually, equivalent to powering 50,000 Austrian households for a year. The electricity will be sourced from two of VERBUND's own Austrian hydropower plants. This PPA aligns with Borealis' goal of sourcing 100% renewable electricity for its Polyolefins and Hydrocarbons business areas by 2030 and will significantly reduce Scope 2 emissions by approximately 75,000 tons/year at Borealis' Schwechat site. The partnership reflects a commitment to sustainability and the energy transition in Austria and Europe[91].

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[89] https://cefic.org/a-pillar-of-the-european-economy/landscape-of-the-european-chemical-industry/austria/

[90] https://doi.org/10.2908/SBS_R_NUTS06_R2

[91] https://www.borealisgroup.com/news/borealis-and-verbund-sign-first-long-term-hydropower-ppa-to-supply-borealis-operations-in-schwechat-austria-as-of-january-2023

8.3.2 Germany

Background

The chemical industry in Germany holds significant importance and has a long-standing history. In 2018, it achieved an impressive turnover of almost 203 billion euros, with a workforce of over 460,000 employees. Most of the larger companies have expanded their operations globally. The industry offers a diverse range of products, including inorganic basic chemicals, petrochemicals and derivatives, polymers, fine and specialty chemicals, detergents and personal care products, as well as pharmaceuticals.

Some of the major players in the German chemical industry were established as far back as the 19th century. A few of them were once part of IG Farben AG, which was the world's largest chemical company at that time. However, following the Second World War, IG Farben faced dissolution due to its involvement in the Third Reich. Despite this historical event, the German chemical industry continues to thrive, and here is an overview of the 10 largest German chemical companies in the present day.

Top regions (employment share in all manufacturing)[92]

- Darmstadt (16.0%)
- Dusseldorf (13.9%)
- Koln (11.9%)

Example

Plastics offer evident advantages during their usage, such as food preservation, lightweight vehicles, and building insulation. However, the challenge of plastic waste has grown significantly, with approximately 250 million metric tons generated globally annually. Just 20% of this plastic is recycled, highlighting the need for increased recycling efforts. Addressing this challenge and establishing a more circular plastic economy demands innovation and collaboration across the value chain.

BASF is actively contributing to this effort through innovative technologies and products designed to promote plastic recycling. A central initiative is the ChemCycling® project, centered around pyrolysis technology that converts plastic waste and end-of-life tires into pyrolysis oil. This secondary raw material is integrated into BASF's Verbund production, conserving fossil resources. A third-party audited mass balance approach attributes the recycled feedstock share to Verbund-manufactured products. These certified Ccycled® products possess identical properties to conventional items, enabling customers to use them similarly in demanding applications.

ChemCycling® primarily targets plastic waste not suited for mechanical recycling due to technical, economic, or ecological reasons. This includes plastics with residues, unsorted mixed plastic fractions, and non-recycled scrap tires. The project aligns chemical and mechanical recycling to enhance overall recycling rates and promote a more circular plastic economy.

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[92] https://doi.org/10.2908/SBS_R_NUTS06_R2

8.3.3 Italy

Background

Italy’s Chemical manufacturing contributes 9.5% to the overall chemical production in Europe and holds the 12th position globally. In specific sectors like fine chemicals and specialties, Italy achieves even higher rankings, including global leadership in pharmaceutical active ingredients.

As a country with a strong industrial background, Italy stands as the third-largest market for chemicals within the European Union. Its strategic location in the middle of the Mediterranean Sea provides advantageous access, leading many foreign-owned chemical companies to establish their Southern Europe headquarters there.

Italy boasts a substantial presence in the chemical industry, with over 2,800 active companies operating across the country. These companies employ more than 112 thousand highly qualified individuals, showcasing the industry's significant contribution to employment and expertise within Italy[93].

Top regions (employment share in all manufacturing)[94]

- Molise (5.2%)
- Lombardia (5.0%)
- Trento (4.0%)

Example

Solvay has entered into a 10-year Corporate Power Purchase Agreement (PPA) with Falck Renewables S.p.A for a solar project in Puglia, Italy. The upcoming 41.1 MW solar plant is set to generate approximately 70 GWh of electricity annually, equivalent to powering about 26,000 households. Notably, 70% of the solar plant's electricity will supply four of Solvay's Italian sites, namely Bollate, Ospiate, Livorno, and Rosignano. This transition to green energy is projected to cut annual CO2 emissions by over 15,000 tons.

The project innovatively blends renewable energy generation and agricultural activity, featuring a combination of solar panels and rows of olive trees. This integration will also create new jobs and local revenues through the management of the olive grove.

Marco Colatarci, Solvay's Country Manager in Italy, expressed pride in the company's move towards solar energy for the majority of its Italian facilities, emphasizing the alignment with Solvay's ambitious sustainability goals outlined in the Solvay One Planet roadmap.

This initiative falls within Solvay's broader sustainability roadmap, aiming to reduce greenhouse gas emissions by 26%. Toni Volpe, CEO of Falck Renewables, highlighted the project's synthesis of technology and agriculture to support industrial clients' sustainability objectives, contributing to a greener future[95].

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[93] https://www.federchimica.it/docs/default-source/chemical-industry-in-italy/the-chemical-industry-in-italy-2019_web.pdf?sfvrsn=c8474093_4

[94] https://doi.org/10.2908/SBS_R_NUTS06_R2

[95] https://www.solvay.com/en/news/solvay-ramps-solar-energy-italian-sites

8.3.4 The Netherlands

Background

The Netherlands hosts a robust chemicals industry positioned as Europe's third largest. This strength is attributed to key factors including Rotterdam harbour, well-established infrastructure, prestigious universities, and a skilled workforce, which have all attracted major global chemical corporations.

Remarkably, the chemical sector is a significant employer, contributing to a turnover of EUR 71 billion in 2019. With over 380 companies and 45,000 employees, it ranks as the Netherlands' second-largest industry. The country stands at the forefront globally in fundamental chemistry, biotechnology, food ingredients, coatings, and high-performance materials. The chemical industry plays a pivotal role in the nation's exports, accounting for nearly 19%. The Dutch chemical industry is driven by innovation, investing a substantial EUR 1 billion annually in research and development, solidifying its position as a leading innovator in the global landscape[96].

Top regions (employment share in all manufacturing)[97]

- Zeeland (18.2%)
- Limburg (10.9%)
- Groningen (10.3%)

Example

Ørsted, a prominent offshore wind developer, and Yara, a leading fertilizer company, have partnered to pioneer a project focused on replacing fossil hydrogen with renewable hydrogen in ammonia production. This initiative could potentially reduce over 100,000 tonnes of CO2 annually, equivalent to removing 50,000 conventional cars from the road. Pending public co-funding and regulatory support, the project aims to become operational by 2024/2025.

The collaboration aims to create a 100 MW wind-powered electrolyser plant for producing renewable hydrogen. This renewable hydrogen will replace fossil-based hydrogen in Yara's Sluiskil plant in the Netherlands, generating around 75,000 tons of green ammonia per year. The ammonia will be used in carbon-neutral fertilizer production and holds potential as a climate-neutral shipping fuel.

Although renewable hydrogen production is more expensive than fossil-based hydrogen currently, Ørsted and Yara intend to bridge this cost gap with public co-funding. They plan to seek funding for the 100MW electrolyser facility to advance the project. If sufficient funding is secured and a viable business case is confirmed, the final investment decision could be made by late 2021 or early 2022.

This initiative aligns with the Netherlands' ample offshore wind resources and hydrogen consumption centers, positioning the country as a leader in green industrial transformation. It also contributes to the scaling of renewable hydrogen production towards 3-4 GW by 2030, marking a significant step in the Dutch hydrogen roadmap[98].

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[96] https://cefic.org/a-pillar-of-the-european-economy/landscape-of-the-european-chemical-industry/netherlands/

[97] https://doi.org/10.2908/SBS_R_NUTS06_R2

[98] https://www.yara.com/corporate-releases/orsted-and-yara-seek-to-develop-groundbreaking-green-ammonia-project-in-the-netherlands/

8.3.5 Poland

Background
The chemical industry holds a significant position within the Polish economy, constituting 16.9% of the total industry. Over the past decade, it has shown remarkable growth, ranking as one of the fastest-growing sectors in the country. The chemical sector's average annual sales growth rate from 2009 to 2021 stood at 4.9%. In 2021, the total sales of the Polish chemical industry, including products like coke, refined petroleum, pharmaceuticals, rubber, and plastics, amounted to 75 billion EUR. This figure represents an impressive 39% increase compared to the value in 2020. Poland's chemical production is widely distributed across the country, with major domestic producers operating manufacturing plants throughout different regions. To enhance cost-effectiveness and competitiveness, processing plants are often situated close to companies producing chemicals in their primary forms. This strategic approach aims to reduce transport costs and streamline production processes[99]. • The production facilities of the largest domestic manufacturers are located all over the country; the production of the chemical industry in Poland is characterized by a high degree of dispersion. Processing plants are often located close to the companies that produce the primary forms of the chemicals used in processing. This is due to reducing transportation costs and increasing competitiveness.
Top regions (employment share in all manufacturing)[100]
• Lubelskie (6.0%) • Warszawski Stołeczny (5.9%) • Zachodniopomorskie (5.5%)
Example
Covestro has developed an innovative chemical recycling process for polyurethane (PU) flexible foam found in used mattresses. The process, developed in collaboration with the PUReSmart project coordinated by Recticel, allows for the recovery of both important raw materials present in mattresses' foam. A pilot plant for flexible foam recycling has been initiated at Covestro's Leverkusen site to validate positive laboratory results. This technology aligns with Covestro's circular economy vision and commitment to reducing the carbon footprint of materials while addressing plastic waste. The project also includes an intelligent sorting solution, using algorithms to identify different foam types for effective recycling. This effort advances Covestro's involvement in shaping a circular ecosystem and contributing to the European Union's circular economy and environmental goals[101].

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[99] https://cefic.org/a-pillar-of-the-european-economy/landscape-of-the-european-chemical-industry/poland/

[100] https://doi.org/10.2908/SBS_R_NUTS06_R2

[101] https://www.covestro.com/press/closing-the-loop-for-polyurethane-mattresses-public/

8.3.6 Spain

Background

The Spanish chemical sector contributes significantly to wealth creation and employment. It consists of over 3,120 companies and achieved a turnover of EUR 77,241 billion in 2021, supporting 710,430 direct and indirect jobs. With a remarkable 55% growth in revenue from 2007 to 2021, this industry represents 13.3% of Spain's Gross Industrial Product and contributes 5.4% to the country's GDP.

The Spanish chemical sector is the second most important category in terms of exports, with EUR 44,527 billion worth of products exported to international markets in 2021. Moreover, employment within the sector is characterised by stability, with 93% of contracts being permanent. The chemical industry also demonstrates high productivity per employee, further enhancing its economic impact.

The Spanish chemical sector is projected to experience rapid global growth, with an estimated annual production increase of 4.5% required to meet international demand until 2030. Spain ranks fourth in the number of new projects initiated by multinational companies in the European Union between 2003 and 2021[102].

Top regions (employment share in all manufacturing)[103]

- Cataluna (8.5%)
- Este (7.7%)
- Comunitat Valenciana (6.9%)

Example

Spanish multi-energy company Repsol is teaming up with Montreal-based Enerkem and global water and waste management expert Agbar to establish the Ecoplanta project. The project aims to construct a waste-to-chemicals plant in Tarragona, Spain. Operating as the Ecoplanta Molecular Recycling Solutions joint venture, the plant is designed to process approximately 400,000 tons of non-recyclable municipal solid waste from the local area, producing 220,000 tons of methanol. This methanol will serve as a raw material for generating circular materials or advanced biofuels, leading to the avoidance of 200,000 tons of CO2 emissions and reducing landfill waste.

The plant, a pioneering endeavor in the Iberian Peninsula, will be co-managed by Repsol and Agbar, with Enerkem serving as the crucial technological partner. Plans anticipate its operation to commence in 2025, following the final investment decision scheduled for the first quarter of 2022. The project has already received Integrated Environmental Authorization and the approval of the Environmental Impact Statement from local authorities. Repsol's significant industrial complex in Tarragona will enable synergies with the new plant. The complex is a vital petrochemical hub in Spain, known for producing various specialized polymers, including those tailored for the automotive sector. The plant will employ Enerkem's proprietary gasification technology to transform heterogeneous municipal solid waste into valuable products such as methanol. Repsol's involvement reflects their commitment to circular economy principles, aiming to recycle 20% of their polyolefins production by 2030[104].

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[102] https://www.investinspain.org/en/industries/chemical-industry

[103] https://doi.org/10.2908/SBS_R_NUTS06_R2

[104] https://www.repsol.com/en/press-room/press-releases/2021/repsol-to-join-enerkem-and-agbar-to-build-a-waste-to-chemicals-plant-in-tarragona/index.cshtml

8.4 Expert interviews

Here we present more details from the interviews with the experts. Each expert was asked to identify 1 to 3 emerging technologies in their field and assess their decarbonization potential, limitations, and other considerations. The responses were collected in a tabular format which is presented below for each technology grouping.

Table 5: Decarbonization technologies and their potential

Technology or solution	**Decarbonization strategy:** **1.Energy efficiency** **2.Material efficiency** **3.Fuel switching** **4.Circular economy**	**Technology readiness level (0-9)**	**Potential decarbonization application**
Hydrogen Direct Reduction of Iron	Fuel switching	7	• Production of sponge iron that can be directly used in the electric arc furnace for steel production. • Allows to produce steel using hydrogen as fuel and reduction agent instead of coal
3D Concrete Printing	Material efficiency	6/7	• Printing buildings • Printing prefabricated elements
Digital twin	Energy efficiency Material efficiency Circular economy	Uncertain, it depends on the application sector	• Virtualization of production processes • Virtual testing of materials and plants • Real time identification of energy consuming processes and inefficiencies • Identification of production process limits • Raw materials supply tracking and shortages prevision • Buildings life cycle assessment • Enhance transportation fuel consumption efficiency • Smart homes interactions and behaviour automatization • Energy consumption monitoring in smart homes • Prediction on consumes of industrial plants • Preventive substitution of production process plants parts • Suggestion of substitutive materials in production • Virtual testing of materials
Strength enhancers additives	Material efficiency Energy efficiency	9	• Chemically increase the concrete resistance and durability with less cement needed, keeping the same level of performance
Geopolymers	Material efficiency Circular economy Energy efficiency	2	• Used in buildings as an alternative to traditional Portland cement
Inert Anode	Material efficiency Fuel switching	6	• They replace consumable carbon anodes with ceramic or alloys anodes, significantly

	Energy efficiency		reducing greenhouse gas emissions associated with aluminum production
Crop rotation with cover crops	Circular economy Material efficiency	9	• Reduced utilization of synthetic fertilizers as external inputs which are heavily dependent on fossil fuels
Product quality relaxation (size, colour, shape)	Material efficiency	theoretical level, some testing	• Reducing food waste can help reduce the use of resources for production and also reduce the GHG emission from food waste in landfills
Precision agriculture	energy/material efficiency	Deployed in large-scale farms	• Reduce inputs like fertilizers
Renewable energy integration	Fuel switching	8	• Reduce energy input
Small scale, community-based biogas generation from agricultural waste	Fuel switching Circular economy	9	• By replacing natural gas for heating, biogas can substantially reduce GHG emissions.

Table 6: Decarbonization technologies and their benefits and limitations

Technology or solution	Benefits	Limitations
Hydrogen Direct Reduction of Iron	• If the electricity used for electrolysis is obtained from renewable sources, the process is carbon neutral. • The process output can be used in the electric arc furnace to produce steel, this allows to electrify the entire steel production process. • The process in linear, the iron is not transformed in pig iron like in the blast furnace.	• the production cost is higher with respect to the traditional route (blast furnace) • the production capacity is lower (with respect to the traditional route (blast furnace) • Hydrogen is difficult to stock and handle
3D Concrete Printing	• It allows the building of walls with hollow sections. • The material saved could compensate for the higher cement content in the concrete. • Provides more choices for the materials used in the concrete mixture, allowing less carbon-intensive concrete manufacturing. • It allows unique geometric shapes in buildings.	• Printable concrete mixtures contain more cement than normal concrete and the carbon content is higher. • The technology is still immature and the possible future application on a large scale is uncertain. • Printable Concrete is more expensive than normal concrete. • Requires highly specialised to build with this technology.
Digital twin	• Predictive maintenance of production plants allows a continuative production process • Energy efficiency behaviours suggestions • Material efficiency behaviours suggestions • Very flexible technology, it can be applied across all sectors • Production process optimization and resilience • Reduction of material and energy consumed • Avoiding raw material shortages and the subsequent production process stop	• Nowadays there is not a unique definition of digital twin • Digital twin needs energy to work and the energy efficiency effect is difficult to estimate • Continuous data flow between physical and virtual objects. • Data privacy issues and hackers risks • Need of hardware and software constant update • Complex user accessibility • Not completely integrated in the production processes • High energy consumption (but compensated by the energy savings. In big corporations the energy savings should be bigger then the additional energy consumed by the technology) • Interoperability problems
Strength enhancers additives	• Reduced energy consumption and lower CO_2 emissions allowing a less cement percentage in concrete production • Enhance the strength of different cement formulations	• The regulation constrains the minimum amount of cement in the concrete.
Geopolymers	• Favorable durability properties • Reduce CO_2 emissions during production compared to normal cement. • Excellent mechanical strength	
Inert Anode	• It only emits oxygen (O_2)	• widespread adoption of inert anodes in existing aluminium smelters requires further research and development.

	• Improved energy efficiency due to reduced energy losses associated with carbon anodes • Longer lifespan and reduced anode replacement costs.	
Crop rotation with cover crops	• Legumes can be used as feed, reduced cost as a result of reduced reliance on fertilizers	• More knowledge and training for farmers are needed about crop rotation, more machinery should be deployed
Product quality relaxation (size, colour, shape)	• Increase food cycle efficiency	• Public acceptance, regulations
Precision agriculture	• Decrease fertilizer, pesticides and herbicides use	• Only available in large farms
Renewable energy integration	• Decrease fossil energy input	• Needs oil crops or other renewable sources
Small scale, community-based biogas generation from agricultural waste	• Reducing agricultural waste, generating energy, reducing reliance on foreign-sourced natural gas	• Cost is the main limiting factor, also it takes a long time to coordinate among small farms to invest in this initiative

Table 7: Decarbonization technologies and their barriers

Technology or solution	Policy/regulatory barriers	Technological barriers	Economic barriers	Public acceptance
Hydrogen Direct Reduction of Iron	Low	High	High	Medium
3D Concrete Printing	High	Medium	Medium	Medium/High
Digital twin	Low	High	Medium/High	-
Strength enhancers additives	High	Low/Medium	Low/Medium	Medium
Geopolymers	High	Medium	Low/Medium	Medium
Inert Anode	Low	High	Medium	Low
Crop rotation with cover crops	Medium Eu nature conservation law, lots of bureaucracy , EU soil law proposal (soil health with impact on farmers)	Low Access to varieties of legumes and other crops resistant to climate change impact, precision agriculture using GIS and drones can help reduce the need for fertilizers	High subsidies for smallholder farms (<10 ha) instead of large-scale farms	High
Product quality relaxation (size, colour, shape)	Medium Quality standards for agri products that needs to change or relaxed	Low	Low	Low Public should be educated about food with different look/size/taste
Precision agriculture	Low	Medium	High	Low
Renewable energy integration	Low	Medium	High	Low
Small scale, community-based biogas generation from agricultural waste	High There are over 15 different laws and regulations from different aspects of agriculture, energy, waste, and urbanization.	Low The main technology is simple and mature	High for small farmers it is a high cost even with the existing EUR ~150 per MWh feed-in-tariff	Low Strong opposition to intensive farming and animal treatment