The Path to Net-Zero Emissions

A Comparative Analysis of Carbon Capture and Hydrogen Technologies in Hard-to-Abate Sectors

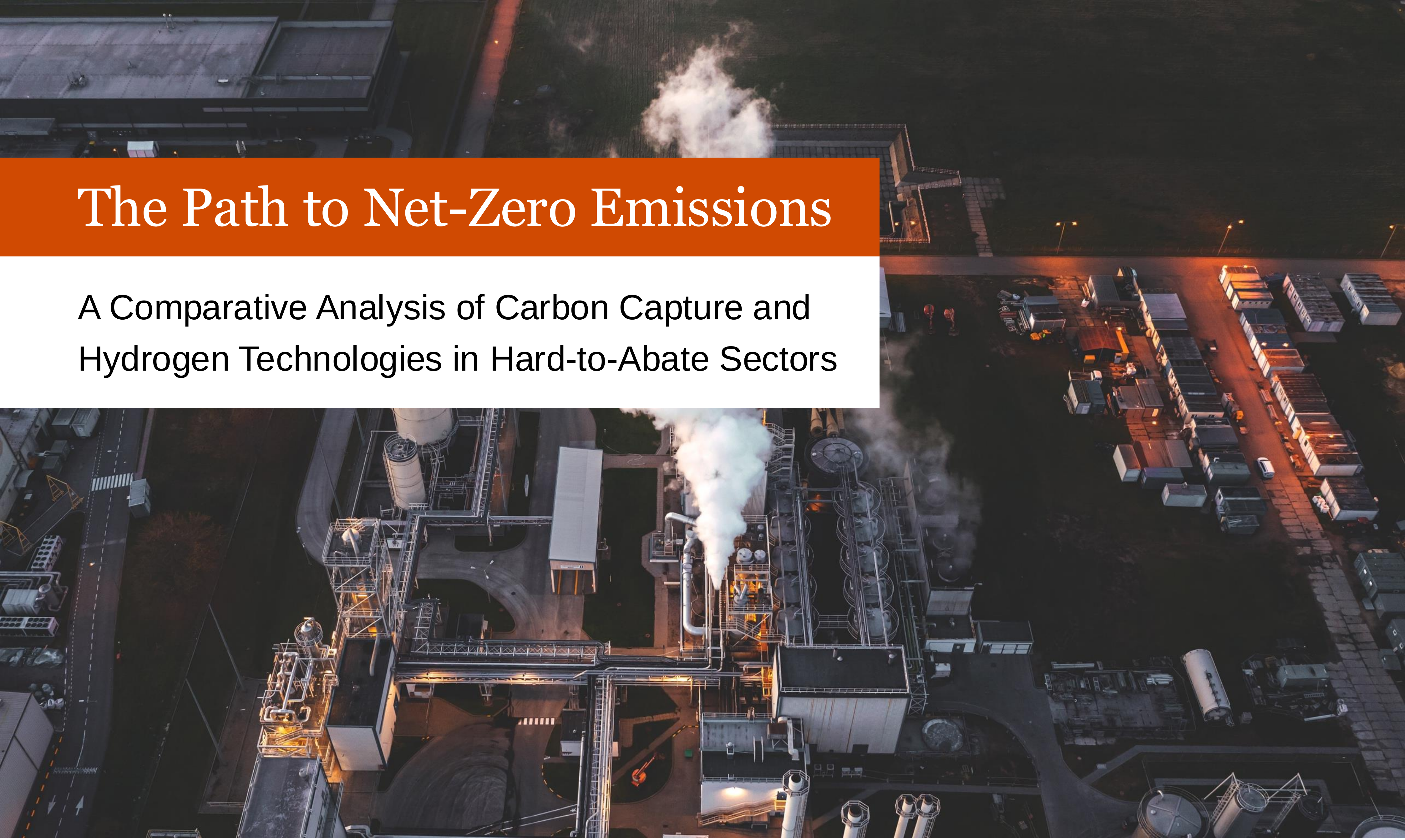

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Table of Content

List of Figures

List of Tables

List of Case Studies

Abbreviations and Acronyms

Abbreviation	Meaning		
\$	Dollar	FCETs	Fuel Cell Electric Trucks
€	Euro	GHG	Greenhouse Gases
BF - BOF	Blast Furnace - Basic Oxygen Furnace	GH_2	Green Hydrogen
BECCS	Bioenergy with Carbon Capture and Storage	GCCA	Global Cement and Concrete Association
BET	Battery Electric Trucks	H_2	Hydrogen
CaCO3	Limestone	H_2 - DRI	H_2 -Based Direct Reduced Iron
CaO	Lime	HRS	Hydrogen Refueling Infrastructure
CBAM	Carbon Border Adjustment Mechanism	IEA	International Energy Agency
CCS	Carbon Capture and Storage	IRENA	International Renewable Energy Agency
CCUS	Carbon Capture, Utilization and Storage	LNG	Liquefied Natural Gas
CEMBUREAU	European Cement Association	MOF	Metal - organic Frameworks
CO_2	Carbon Dioxide	NZE	Net-Zero Emissions
DAC	Direct Air Capture	RAF	Royal Air Force
DRI - EAF	Direct Reduced Iron-Electric Arc Furnace	SAFs	Sustainable Aviation Fuels
EAF	Electric Arc Furnace	SMR	Steam Methane Reforming
EOR	Enhanced Oil Recovery	TRL	Technological Readiness Level

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Foreword

In the race to combat climate change, some of the most challenging sectors to decarbonize are those where traditional solutions, like electrification, fall short. To address this, innovative technologies like hydrogen (H_2) and carbon capture, utilization, and storage (CCUS) have emerged as crucial tools. This report explores the powerful potential of combining these technologies to reduce emissions and accelerate the global transition to a net-zero economy.

By focusing on sector-specific solutions, we can harness the complementary strengths of H_2 and CCUS to tackle emissions in industries that are traditionally hard to decarbonize. While the path forward is not without its challenges—especially in terms of costs and scaling—these technologies present a unique opportunity to make significant strides in emission reductions, particularly where other methods are less effective.

As this report illustrates, the synergy between H_2 and CCUS can reshape how we approach climate action, providing both environmental benefits and new economic opportunities. With the right investments and innovations, this combined approach can be a key driver in achieving a sustainable, low-carbon future.

Executive Summary

The decarbonization of hard-to-abate sectors necessitates the synergistic deployment of hydrogen (H_2) and carbon capture, utilization, and storage (CCUS) technologies. This paper hypothesizes that a sector-specific approach leveraging the strengths of these technologies can effectively reduce emissions while addressing economic and technical barriers.

Achieving net-zero greenhouse gas emissions is a global priority, particularly in hard-to-abate sectors where traditional decarbonization strategies face significant challenges. This report explores the critical roles of low-carbon hydrogen and CCUS technologies in driving meaningful progress toward a net-zero future. These solutions, when applied in synergy, offer transformative potential for industries where electrification is limited or impractical.

CCUS technologies, especially in blue hydrogen production through Steam Methane Reforming (SMR), are at the forefront of emission reduction strategies. Blue hydrogen production, while inherently emission-intensive, can achieve substantial greenhouse gas reductions—exceeding 80%—when integrated with advanced carbon capture systems. This dual approach captures carbon dioxide (CO_2) generated during hydrogen production and stores or repurposes it, preventing its release into the atmosphere.

The decarbonization of hard-to-abate sectors—steel, aluminum, cement, petrochemicals, heavy transport, and aviation—requires the synergistic deployment of both technologies. For example, the H_2H Saltend Project in the UK aims to produce 1 GW-hour of low-carbon hydrogen annually by 2030 using renewable energy-powered electrolysis and steam methane reforming with CCS. In Saudi Arabia, the NEOM Project will produce 650 tons of green hydrogen daily using solar and wind energy, establishing a hydrogen hub for production, storage, and transportation. The Northern Lights Project in Norway integrates hydrogen production with CCS to capture and store CO_2 beneath the North Sea. These sector-specific solutions demonstrate the potential of hydrogen and CCUS to decarbonize industries where electrification is impractical.

The HYBRIT initiative launched by SSAB, LKAB and Vattenfall produced hydrogen-reduced sponge iron, eliminating 90% of emissions from steelmaking process. The cement industry is also advancing with Lehigh Cement's planned CCUS plant, expected to capture 95% of emissions by 2026. Similarly, the Antwerp@C Project in Belgium focuses on CO_2 infrastructure for the petrochemical sector, aiming to reduce emissions by 50% by 2030. Hydrogen fuel cell trucks are being tested through initiatives like the H_2Haul Project, which focuses on establishing hydrogen refueling infrastructure across Europe.

These efforts underscore the critical role of CCUS and hydrogen in decarbonizing hard-to-abate sectors, demonstrating both their transformative potential and the challenges in scaling these technologies for a net-zero future. This report highlights the emergence of CCUS hubs incorporating hydrogen initiatives, leveraging their complementary benefits to decarbonize hard-to-abate industries. While cost considerations remain a barrier, the environmental and economic potential of these technologies is undeniable. The findings emphasize that CCUS and hydrogen are essential components of a multifaceted strategy to mitigate climate change and accelerate the transition to a sustainable, net-zero future.

The table 1 provides a concise summary of the key insights discussed throughout the paper. It captures the feasibility and readiness of H_2 and CCUS technologies across various sectors, offering a clear comparison of their strengths, limitations, and the challenges they face in driving decarbonization efforts.[1]

Table 1 Comparison of Hydrogen (H_2) and Carbon Capture, Utilization, and Storage (CCUS) Implementation Feasibility Across Hard-to-Abate Sectors

Sector	H_2 (Hydrogen)	CSUS (Carbon Capture, Utilization and Storage)
Steel Industry	Viable for direct reduction with green H_2 but faces high energy demands.	Proven for integration with blast furnaces but expensive and less transformative.
Aluminum Industry	Feasible for indirect heat but highly limited by production cost barriers.	Captures smelting emissions but competes with electrification alternatives.
Cement Industry	Promising for carbon-free combustion but constrained by high costs of green hydrogen.	Effective for capturing process emissions, though costly and at early maturity.
Petrochemicals	Key for refining and transitional blue H_2; infrastructure gaps persist.	High efficiency in capturing process emissions but costly with limited reductions so far.
Heavy Transport	Suitable for long-haul trucking and shipping; refueling infrastructure remains costly.	Limited application due to high costs of Direct Air Capture (DAC) and synthetic fuel production.
Aviation	Hydrogen fuels and propulsion have potential but are at low TRL.	Synthetic jet fuels are critical near-term options, hindered by DAC and storage costs.

Least Relevant — Most Relevant

[1] PwC Analysis

1 A Unified Overview of CCUS and Hydrogen Technologies

The 2015 Paris Agreement, supported by broad international consensus in response to accelerating global climate change, has placed addressing climate change at the forefront of the global agenda. As governments worldwide announce net-zero emission targets, the need for widespread deployment of clean energy technologies to achieve deep decarbonization is growing.

However, many industrial and transport sub-sectors remain significant greenhouse gas (GHG) emitters and are more challenging to decarbonize due to their physical, technological, or market-specific characteristics. Significant emission reductions in these "hard-to-abate" sectors will be possible through the deployment of two key clean energy technologies: **hydrogen (H_2) and carbon capture, utilization, and storage (CCUS).**

Figure 1 Hard-to-Abate Sectors

To reduce industrial CO_2 emissions, substantial progress is needed in both hydrogen production and transmission and CCUS technology infrastructure. The timeline for these advancements, however, remains uncertain. Relying on hydrogen alone to make a major short-to-medium-term impact on emissions may not be realistic. To unlock hydrogen's long-term decarbonization potential, clear commitments are needed for advancing CCUS and renewable energy technologies in the near future.[2]

1.1. What is Carbon Capture / CCUS Technology?

Carbon Capture, Utilization, and Storage (CCUS) is a critical process for reducing CO_2 emissions, particularly from hard-to-abate sectors. CCUS implementation consists of four main phases: capture, transport, storage and utilization. [3,4]

1. Capture: This phase involves capturing CO_2 emissions from major sources such as power plants, industrial facilities, or even directly from the air. The most common method of capture is artificial capture, used in industrial and power plant settings.

2. Transport: Once captured, the CO_2 must be transported for either storage or reuse. The most cost-effective transport method is via pipelines, many of which are already in place. For example, North America has an existing 800 km pipeline system. Alternatively, CO_2 can be compressed into a liquid form and transported by road, rail, or ship.

3. Storage: If the CO_2 is not repurposed, it is stored long-term in depleted oil or gas reservoirs or deep underground geological formations. These sites ensure that the CO_2 remains safely contained, preventing it from re-entering the atmosphere.

4. Utilization: Captured CO_2 can be utilized as a feedstock in various industrial processes, contributing to the development of products and services while supporting emission reduction goals further.

[2] Committees.parliament.uk. (n.d.). Publications: The role of carbon capture in the UK economy. Retrieved from https://committees.parliament.uk/publications/33292/documents/180198/default/
[3] International Energy Agency (IEA). (n.d.). Carbon capture, utilisation, and storage. Retrieved from https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage
[4] Energy Advice Hub. (n.d.). Hydrogen and CCUS: Everything your business needs to know. Retrieved from https://energyadvicehub.org/hydrogen-and-ccus-everything-your-business-needs-to-know/

There are several key technologies currently in use for carbon capture, each playing a distinct role: [5,6]

Industrial-Point-Source CCUS

This technology is the most immediate solution for decarbonization, as it is already available and can capture significant amounts of CO_2 from industries that are difficult to decarbonize.

Direct air capture (DAC)

Although still under development, DAC has great potential for large-scale carbon removal, especially when integrated with other emerging technologies such as hydrogen production or sustainable aviation fuel. To date, 27 DAC plants have been commissioned globally, capturing approximately 0.01 Mt of CO_2 per year.

Bioenergy with carbon capture and storage (BECCS)

BECCS is expected to play a crucial role in achieving net-zero emissions, particularly as natural carbon removal solutions reach their limits. Currently, BECCS captures about 2 Mt of biogenic CO_2 annually, mainly used in bioethanol production.

In this context, the development of new markets for decarbonized hydrogen products is further driving the expansion of CCUS projects. Hydrogen, particularly blue hydrogen, is seen as a promising clean fuel, especially for energy storage to balance periods of low renewable energy output. Blue hydrogen is produced through steam reforming of natural gas, a cost-effective method, but it generates significant CO_2 emissions. Integrating CCUS with hydrogen production can help reduce these emissions, though the CO_2 capture process remains costly and energy intensive.[7]

[5] International Energy Agency (IEA). (n.d.). Direct air capture. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture
[6] ScienceDirect. (2021). Energy policy: Carbon capture in the context of energy transitionhttps://www.sciencedirect.com/science/article/abs/pii/S030142152100416X
[7] Schlumberger. (n.d.). Scaling the mountain to global CCUS and low-carbon hydrogen production. https://www.slb.com/resource-library/insights-articles/scaling-the-mountain-to-global-ccus-and-low-carbon-hydrogen-production

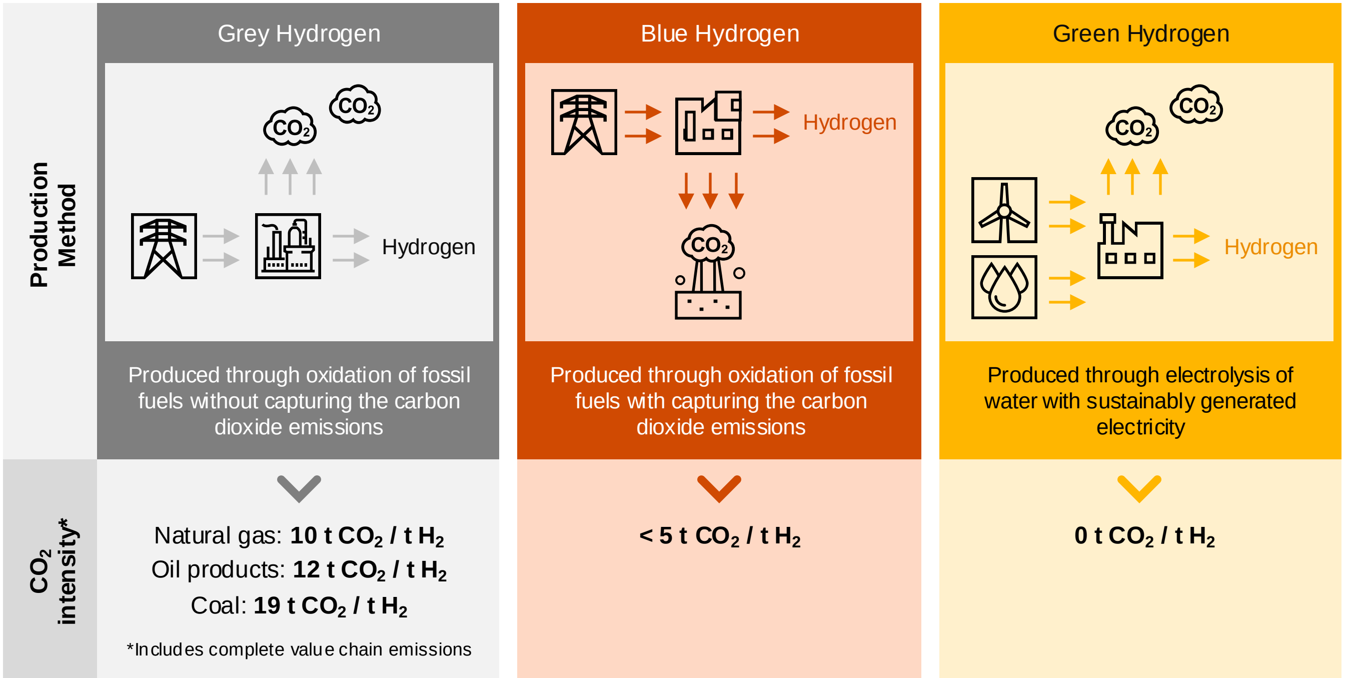
1.2. What is Hydrogen Technology?

Hydrogen, particularly green and low-carbon hydrogen, is increasingly seen as a crucial component in decarbonizing hard-to-abate industries such as steel, cement, and aviation. Currently, hydrogen is produced on a large scale for industrial production, including ammonia and fertilizer manufacturing. However, much of this hydrogen is "grey hydrogen," produced from fossil fuels, which results in significant CO_2 emissions—around 830 million tons annually.[8]

The potential for **green hydrogen** to replace traditional hydrogen is significant, particularly in sectors such as sustainable fertilizer production and material recycling, including polymers. Green hydrogen could also replace natural gas in high-temperature industries like glass, steel, and cement production. However, transitioning these industries to hydrogen will require substantial investment, as well as financial incentives to offset the additional costs of switching from natural gas.[9]

The demand for hydrogen has grown rapidly, tripling since 1975, and is expected to continue expanding. From 2020 to 2022 alone, hydrogen demand grew by 60%, reaching 144 million tons annually. To meet the 1.5°C climate target, the International Renewable Energy Agency (IRENA) estimates that global hydrogen production must rise to 614 million tons annually by 2050, with nearly all of it coming from renewable sources.

Figure 2 Hydrogen Production Types



However, this transition faces several challenges, especially in **developing countries,** where market uncertainties, technical barriers, and political or social issues hinder the development and adoption of green hydrogen technologies.[10]

Currently, **low-emissions hydrogen** is expensive, but costs are expected to decrease significantly over time as the sector develops. However, there is still considerable uncertainty surrounding future costs.

Recent data has led to an upward revision of current electrolyser costs, and the pace of cost reductions will depend on various factors, particularly technological advancements and deployment speed. In the International Energy Agency's (IEA) Net Zero Emissions by 2050 (NZE) Scenario, the cost of producing low-emissions hydrogen from renewable electricity is projected to drop to USD 2-9/kg H_2 by 2030, roughly half of today's price. In Türkiye's Hydrogen Strategy (2024) prices for hydrogen (green) is expected to decrease to under $2.3 per kilogram by 2035 and further to under $1.2 per kilogram by 2053.[11] The cost gap between low-emissions hydrogen and unabated fossil-based hydrogen will also narrow.

[8] World Bank. (2023). Green hydrogen in industry: The potential for sustainable development. https://documents1.worldbank.org/curated/en/099041823103013605/pdf/P1711730c77a380bd0bf340b299f884cf4b.pdf
[9] Committees.parliament.uk. (n.d.). Publications: The role of carbon capture in the UK economy. https://committees.parliament.uk/publications/33292/documents/180198/default/
[10] United Nations Industrial Development Organization (UNIDO). (2023). Green hydrogen in industry: Pathways for development https://www.unido.org/sites/default/files/unido-publications/2023-11/UNIDO%20and%20Green%20Hydrogen%20in%20Industry.pdf
[11] Hypat. (2024). Country report on Turkey's hydrogen economy. https://hypat.de/hypat-wAssets/docs/new/publikationen/HyPAT_Country-Report_Turkey.pdf

On the other hand, as natural gas prices decline in many regions, **hydrogen production from natural gas with CCUS** will also become more affordable. While cost reductions will benefit all hydrogen production projects, their impact will vary.

For instance, large-scale electrolyser development could achieve cost reductions similar to those in the NZE Scenario, with several Chinese and European projects potentially producing hydrogen from electrolysis at a lower cost than coal-based hydrogen.[12]

Decarbonizing domestic industries can be achieved by reenginerring operationg in sectors such as chemicals, steel, cement, aviation, maritime, and heavy cargo transport to use **green hydrogen (GH_2).** National decarbonization goals, corporate standards set by leading companies in global supply chains, and international trade regulations, such as the **EU's Carbon Border Adjustment Mechanism (CBAM)**, provide strong incentives for these industries to adopt GH_2 as a feedstock or energy source.

This transition is particularly important for economies with large heavy industries, especially those that export to markets with strict decarbonization standards. Additionally, countries with significant mining sectors can reduce their carbon footprint by adopting GH_2, aligning their energy-intensive operations with global decarbonization requirements.[13]

Türkiye is also actively pursuing hydrogen and CCUS technologies as part of its strategy to reduce emissions and transition to a sustainable energy system. The country has developed a national hydrogen strategy focused on both blue and green hydrogen, utilizing its vast renewable energy resources for production. Several pilot projects are underway to test hydrogen in industrial applications and transportation, with an emphasis on energy storage and integration. Türkiye also views CCUS as vital for decarbonizing heavy industries such as cement and steel, with multiple pilot projects targeting CO_2 capture and utilization. The government has included CCUS in its climate policies, exploring storage solutions in suitable geological formations. Through international collaborations, Türkiye is advancing both H_2 and CCUS technologies, aiming to become a key player in the global energy transition. The synergies between these technologies, particularly in blue hydrogen production, offer a pathway to achieving the country's decarbonization goals.

1.3. How can H_2 and CCUS Technologies be combined?

Achieving a net-zero future requires a multi-faceted approach, combining improved energy efficiency, an increased use of renewable energy, and the implementation of CCUS technology. In particular, H_2 and CCUS are complementary technologies that can provide the key solutions needed to decarbonize hard-to-electrify sectors, offering a dual pathway to reducing emissions and driving industrial transformation.[14]

The growing synergy between H_2 and CCUS is at the heart of many emerging CCUS hubs, where the two technologies are deployed together to maximize emission reductions. Blue hydrogen production, in particular, is a key solution for reducing greenhouse gas emissions.[15] It is created from natural gas through a process called steam methane reforming (SMR), which produces both hydrogen and CO_2. For every ton of hydrogen produced, 9 to 12 tons of CO_2 are emitted. Carbon capture technology is used to prevent these emissions from entering the atmosphere by safely capturing and storing the CO_2.[16]

[12] International Energy Agency (IEA). (n.d.). Direct air capture and its potential in carbon-neutral industries. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture
[13] United Nations Industrial Development Organization (UNIDO). (2024). Green hydrogen for sustainable industrial development: A policy toolkit for developing countries. https://www.unido.org/sites/default/files/unido-publications/2024-02/Green%20hydrogen%20for%20Sustainable%20Industrial%20Development%20A%20Policy%20Toolkit%20for%20Developing%20Countries.pdf
[14] Schlumberger. (n.d.). Scaling the mountain to global CCUS and low-carbon hydrogen production. https://www.slb.com/resource-library/insights-articles/scaling-the-mountain-to-global-ccus-and-low-carbon-hydrogen-production
[15] Committees.parliament.uk. (n.d.). Publications: The role of carbon capture in the UK economy. https://committees.parliament.uk/publications/33292/documents/180198/default/
[16] Verde Ag. (n.d.). Blue hydrogen and carbon capture: Innovations in low-carbon energy production. https://blog.verde.ag/en/blue-hydrogen-and-carbon-capture/

Although the process is costly, CCUS remains essential for tackling climate change by either storing CO_2 securely or repurposing it for other applications. This integrated approach, when paired with hybrid solutions, reduces greenhouse gas emissions by over 80% compared to the use of natural gas alone, even without carbon capture, while ensuring flexibility and scalability in achieving net-zero goals.[17]

Looking ahead, the International Energy Agency (IEA) projects that achieving net-zero emissions by 2050 will require large-scale investments in both H_2 and CCUS technologies. However, financial institutions are still cautious, waiting for these technologies to prove their viability in the same way established green technologies have.

Ultimately, the integration of H_2 and CCUS forms a crucial part of the decarbonization puzzle. As hybrid solutions scale up, they will play a vital role in reaching carbon neutrality and paving the way for a sustainable, low-carbon industrial future.

Table 2 Cases with Hydrogen and CCUS Technologies

Project Name	Country	Technology	Description
H_2H Saltend project	United Kingdom	CCS	By 2030, the project aims to produce 1 GW-hour of low-carbon hydrogen annually, using renewable energy-powered electrolysis and steam methane reforming with carbon capture and storage.
NEOM project	Saudi Arabia	Hydrogen	The project will produce 650 tons of green hydrogen daily using solar and wind energy. It aims to establish a hub for hydrogen-related goods production and develop infrastructure for hydrogen storage and transportation.[18]
Northern Lights Project	Norway	CCS	The Northern Lights project is a carbon capture and storage (CCS) initiative that integrates hydrogen production to support decarbonization. A collaboration between Equinor, Shell, and TotalEnergies, it is part of Norway's Longship project. The project aims to capture CO_2 emissions from industrial sources, transport them, and store them safely beneath the North Sea.[19]

[17] Verde Ag. (n.d.). Blue hydrogen and carbon capture: Innovations in low-carbon energy production. https://blog.verde.ag/en/blue-hydrogen-and-carbon-capture/
[18] ScienceDirect. (2024). Energy policy: A critical review of carbon capture technologies. https://www.sciencedirect.com/science/article/pii/S0254058424008356
[19] Equinor. (n.d.). Northern Lights: Carbon storage and its role in decarbonization. https://www.equinor.com/energy/northern-lights

2 Evaluating CCUS and Hydrogen Technologies Across Hard-to-Abate Industries

Both hydrogen and CCUS technologies hold significant potential in **hard-to-abate industries,** particularly those that rely on fossil-fuel-derived energy, such as steel, cement, aluminum, petrochemical, heavy transport and aviation sectors. **Green hydrogen (GH_2)** offers a solution for decarbonizing these industries by providing high-grade heat fuel and serving as a key feedstock for various industrial processes. Integrating **CCUS** with hydrogen production, especially for blue hydrogen, can further reduce emissions by capturing CO_2 at the point of production and either storing it underground or repurposing it for other uses. The synergy between these two technologies not only provides an efficient energy carrier but also offers long-term storage to mitigate the intermittency of renewable energy sources like **solar and wind,** making them essential for stabilizing energy grids and ensuring a reliable power supply.[20]

The success of hydrogen adoption in these sectors hinges on various factors, **including cost competitiveness** and **infrastructure development**. For example, the viability of hydrogen fuel cell vehicles and trucks depends on the reduction of fuel cell costs and the expansion of refueling stations.

Moreover, CCUS can help decarbonize hydrogen production from natural gas, ensuring that the hydrogen used in these sectors is low-carbon. Additionally, hydrogen can be integrated into existing natural gas networks for applications like **district heating, hydrogen boilers, and residential fuel cells.** Ammonia produced from hydrogen can also enhance power system flexibility when integrated into gas turbines or help reduce emissions in coal-fired power plants through CCUS applications.[21]

Hydrogen's primary benefit lies in its potential to decarbonize hard-to-electrify sectors and serve as a clean fuel and feedstock. However, its major bottleneck is the high cost of production, limited infrastructure, and the energy intensity of electrolysis. In contrast, CCUS excels in directly capturing and storing CO_2, making it an effective tool for decarbonizing fossil fuel-based hydrogen production. Yet, its challenges include the high cost of capture and storage infrastructure, as well as the limited availability of suitable storage sites.

[20] Ibid.
[21] Ibid.

This chapter provides a sectoral analysis of H_2 and CCUS in 6 hard-to-abate industries, focusing on their roles in decarbonization. The table below outlines the advantages and challenges of both technologies, offering insights into their capabilities and synergies. Ultimately, this analysis aims to help stakeholders understand how these technologies can complement each other, driving the adoption of low-carbon hydrogen and accelerating the transition to a sustainable industrial future.

Table 3 Pros and Cons of Hydrogen and CCUS by Sectors

Sector	H_2 (Hydrogen)	CCUS (Carbon Capture, Utilization, and Storage)
Steel Industry	**Pros:** DRI with green H_2 viable **Cons:** High energy intensity	**Pros:** Proven with blast furnaces **Cons:** Adds cost without direct fuel replacement
Aluminum Industry	**Pros:** H_2 for indirect heat processes **Cons:** High production costs	**Pros:** Captures emissions from smelting **Cons:** Competes with cleaner electrification techologies
Cement Industry	**Pros:** Carbon-free combustion; large emission cuts **Cons:** High cost of green H_2	**Pros:** Captures process emissions; scalable **Cons:** Expensive infrastructure; nascent techologies
Petrochemicals	**Pros:** Essential for refining; blue H_2 transition potential **Cons:** Gaps in infrastructure	**Pros:** High capture efficiency for process emissions **Cons:** Limited cost reduction so far
Heavy Transport	**Pros:** Suited for long-haul trucking and shipping **Cons:** Expensive refueling infrastructure	**Pros:** Synthetic fuels decarbonize lifecycle **Cons:** Direct Air Capture (DAC) and production costs remain high
Aviation	**Pros:** Future hydrogen fuels; propulsion potential **Cons:** Low TRL for direct use	**Pros:** Synthetic jet fuels critical for near term **Cons:** High costs of DAC and storage

2.1. Steel Industry

The steel industry is one of the largest industrial contributors to global carbon emissions, accounting for 7% to 9% of total anthropogenic CO_2 emissions. In 2024, the world produced 1,882.6 million tons (Mt) of crude steel.[22] Approximately 72% of global steel was produced **using the BF-BOF method**, which involves high emissions due to the use of fossil fuels for melting iron ore.[23] This method results in an average of 2.2 tons of CO_2 emissions per ton of steel produced. In contrast, the **EAF** method, which accounts for around 21% of global steel production, is more energy-efficient and uses electricity to melt scrap steel. This method emits an average of 0.3 tons of CO_2 per ton of steel.

The **DRI-EAF** route, which uses natural gas to reduce iron ore, is responsible for around 7% of global steel production, with emissions of 1.4 tons of CO_2 per ton of steel.[24, 25, 26]

Given the sector's significant contribution to global emissions, a combination of strategies is required for decarbonization. While increasing energy and process efficiency and maximizing scrap utilization will contribute to reducing emissions, breakthrough technologies such CCUS and hydrogen-based steelmaking are crucial to achieving net-zero emissions.

2.1.1. H_2 in Steel

Hydrogen plays a pivotal role in decarbonizing the steel sector, particularly through the hydrogen-based Direct Reduced Iron (H_2-DRI) process. Unlike the traditional BF-BOF method, which uses fossil fuels for the reduction of iron ore, the H_2-DRI process employs hydrogen as a reduction agent, which significantly reduces emissions. Additionally, H_2-DRI operates at lower temperatures (below 1,200°C), well below the melting point of iron.[27]

Among existing technologies, the clean hydrogen-based DRI-EAF technology is considered the most advanced, with a technological readiness level (TRL) 6-8. Studies suggest that this technology could reduce emissions by up to 97%. However, the cost of implementing hydrogen-based steel production is still a significant barrier. Compared to conventional BF-BOF methods, the cost increase could range from 35% to 70%, and the technology is currently available only for small-scale plants.[28]

Several pilot projects are currently exploring the use of hydrogen in steelmaking, while these initiatives show promise, scaling up hydrogen-based steel production will require considerable investment and support.[29]

Case Study 1

Project: HYBRIT
Country: Sweeden
Technology: Hydrogen
Sector: Steel

The HYBRIT initiative, launched by SSAB, LKAB, and Vattenfall, successfully produced hydrogen-reduced sponge iron in 2020, eliminating around 90% of emissions from the steelmaking process. The hydrogen is generated through water electrolysis powered by fossil-free electricity. The project aims for industrial-scale production of fossil-free steel by 2026, with the potential to reduce global CO_2 emissions by 35 million tonnes annually. It also targets reducing Sweden's emissions by 10% and Finland's by 7%. The initiative represents a critical step toward sustainable steel production with minimal environmental impact.[30]

[22] World Steel Association. (2024). Global crude steel production and forecasts for 2024. https://worldsteel.org/media/press-releases/2025/december-2024-crude-steel-production-and-2024-global-totals/#:~:text=to%2Ddate%20aggregate-,2024%20global%20crude%20steel%20production%20totals,2024%20global%20crude%20steel%20production
[23] ScienceDirect. (2023). The decarbonization of heavy industries: Strategies and technologies. https://www.sciencedirect.com/science/article/pii/S1750583623001330
[24] Institute for Energy Economics and Financial Analysis (IEEFA). (2022). Steel sector's decarbonization challenge: A cost analysis. https://ieefa.org/sites/default/files/2022-06/steel-fact-sheet.pdf
[25] Columbia Business School. (2023). Steel industry: Transitioning to net-zero emissions. https://business.columbia.edu/sites/default/files-efs/imce-uploads/CKI/CKI%20Steel%20Overview-v240313.pdf
[26] 3Step Solutions. (2023). Making net-zero steel possible: Challenges and solutions. https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Making-Net-Zero-Steel-possible-steel.pdf
[27] World Economic Forum. (2024). Technologies for a cleaner steel industry. https://www.weforum.org/stories/2024/04/technologies-cleaner-steel-industry/
[28] World Economic Forum. (2023). Net-zero industry tracker 2023: Steel industry update. https://www.weforum.org/publications/net-zero-industry-tracker-2023/in-full/steel-industry-net-zero-tracker/
[29] World Economic Forum. (2024). Technologies for a cleaner steel industry. https://www.weforum.org/stories/2024/04/technologies-cleaner-steel-industry/
[30] SSAB. (2021). HYBRIT: The world's first hydrogen-reduced sponge iron. https://www.ssab.com/en-gb/news/2021/06/hybrit-ssab-lkab-and-vattenfall-first-in-the-world-with-hydrogenreduced-sponge-iron

2.1.2. CCUS in Steel

In addition to hydrogen, CCUS technologies are essential for decarbonizing the steel industry. While the full commercialization of CCUS technologies for steelmaking is expected by 2028, current technologies show the potential for reducing emissions by up to 90% compared to the traditional BF-BOF method. CCUS could even enable negative emissions when combined with Bioenergy Carbon Capture and Storage (BECCS) technology.[31] However, the high cost of CCUS remains a major hurdle. For example, the cost of carbon capture (including transportation and storage) at a steel plant in the U.S. ranged from 40 to 100 USD per ton.[32]

Furthermore, the transportation and storage of captured CO_2 bring additional costs, and the availability of suitable storage sites is a limitation that must be addressed. Despite these challenges, several large-scale CCUS projects are progressing in the steel sector, demonstrating the potential for future scaling. Innovations and investments in infrastructure, alongside policy support, will be crucial in overcoming these obstacles and making CCUS a viable solution for achieving carbon neutrality in steel production.

Case Study 2

Project: Al Reyadah CCUS Facility
Country: United Arab Emirates
Technology: CCUS
Sector: Steel

The Al Reyadah facility is the only commercial-scale CCUS plant currently operational in the steel sector. Located in the UAE, it captures CO_2 from Emirates Steel Arkan's Direct Reduced Iron (DRI)-based production and transports the captured CO_2 for enhanced oil recovery (EOR). The plant has the capacity to capture up to 800,000 tons of CO_2 annually. Despite being operational for seven years, the plant has only captured 20% of Scope 1 and Scope 2 emissions, underscoring the challenges in scaling CCUS technology within the steel industry.[33,34]

[31] Institute for Energy Economics and Financial Analysis (IEEFA). (2024). Carbon capture in the steel sector: The path forward. https://ieefa.org/sites/default/files/2024-04/Carbon%20capture%20for%20steel-April24.pdf
[32] GEM Wiki. (2024). Steel plant construction costs and carbon capture technology. https://www.gem.wiki/Steel_plant_construction_cost#:~:text=At%20the%20current%20CCUS%20price,14%2D36%20billion%20per%20year
[33] Global CCS Institute. (2021). Technology readiness and costs for CCS. https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf
[34] U.S. Department of Energy. (n.d.). Al Reyadah: Carbon capture and storage project in the UAE. https://fossil.energy.gov/archives/cslf/Projects/AlReyadah.html

2.2. Aluminum Industry

The aluminum industry is the world's largest non-ferrous metal sector, responsible for approximately 3% of global direct industrial CO_2 emissions.[35] This sector encompasses a broad range of processes, from raw material extraction and refining to the production of finished aluminum. Notably, the majority of emissions in this sector (71%) stem from the electrolysis stage, with 78% of these emissions being indirect, meaning they come from the electricity used in the process.[36] Globally, aluminum smelters primarily rely on coal (50.4%), hydroelectricity (34.3%), and natural gas (10.5%) for power generation.[37]

Decarbonizing the aluminum sector hinges on controlling the smelting process and reducing emissions from electricity generation. A key strategy is phasing out fossil fuels in favor of cleaner energy sources, such as renewable electricity, or integrating CCUS technologies. In cases where electrification using low-carbon energy isn't feasible, alternative methods like green hydrogen, concentrated solar thermal energy, and CCUS can play significant roles in emission reductions.

2.2.1. H_2 in Aluminum

Hydrogen has emerged as a promising solution for reducing emissions in the aluminum industry, particularly in heating processes. However, its adoption remains limited due to high costs. Currently, fossil fuel-based hydrogen is the cheapest option (~1.5 €/kg), while green hydrogen produced from renewable energy is significantly more expensive (ranging from 3-5 €/kg). Despite this, there is optimism that the cost of green hydrogen will decrease by up to 30% by 2030, potentially reaching cost parity with gray hydrogen in certain regions between 2028 and 2035.[38]

The use of hydrogen as a reducing agent in aluminum production is still in its early stages. While laboratory tests have shown promising results, the practical implementation of this method will require stable hydrogen availability and high temperatures. A notable example is hydro's successful industrial-scale test of green hydrogen as an energy source for aluminum recycling in June 2023. However, due to economic challenges, Hydro has since indicated that green hydrogen will not be a primary focus for its strategic growth.[39]

Case Study 3

Project: ELYSIS
Country: Canada
Technology: Hydrogen
Sector: Aluminium

ELYSIS, a partnership between Alcoa and Rio Tinto, aims to revolutionize aluminium production with zero-carbon technology. The project focuses on using hydrogen to eliminate greenhouse gas emissions from traditional smelting processes. ELYSIS has demonstrated this technology in pilot plants and plans to scale it for industrial use. The breakthrough replaces carbon anodes with a technology that produces oxygen instead of CO_2, making production carbon-free. Once implemented in Canada, it could reduce annual GHG emissions by 7 million metric tons—equivalent to removing 1.8 million cars from the road. Commercial demonstration is expected between 2025 and 2026.[40]

[35] International Energy Agency (IEA). (2023). Tracking aluminium. https://www.iea.org/energy-system/industry/aluminium
[36] International Aluminium. (2024). Aluminium sector greenhouse gas emissions.
[37] International Aluminium. (2024). Primary aluminum smelting power consumption.
[38] Zore, L. (2024). Decarbonisation options for the aluminium industry (Publications Office of the European Union, Luxembourg, JRC136525). https://doi.org/10.2760/880
[39] Luoma, & Jesus. (2024, November 27). Norway's Hydro to phase out green hydrogen, battery businesses. Reuters https://www.reuters.com/sustainability/norways-hydro-phase-out-battery-green-hydrogen-businesses-2024-11-27/
[40] Elysis. (n.d.). What is Elysis? Retrieved from https://elysis.com/en/what-is-elysis#carbon-free-smelting

2.2.2. CCUS in Aluminum

Carbon capture technologies in the aluminium sector are commercially available but still in early stages of development (TRL 3-4). These technologies primarily target emissions from the electrolysis process, utilizing methods like post-combustion capture with amine scrubbing, oxy-fuel combustion, and pre-combustion capture. The captured CO_2 can be used for applications such as enhanced oil recovery, mineralization, or stored in geological formations like deep saline aquifers or depleted oil and gas reservoirs, where the storage technology is more mature (TRL 5-9). The cost of carbon capture from aluminum smelters can exceed €100 per tonne of CO_2 captured, while in alumina refineries, where CO_2 concentrations are higher, costs tend to range between €50-80 per tonne. Despite these advancements, there is a lack of large-scale industrial studies on CCUS in the aluminium sector.[41]

Case Study 4

Project: Carbon Capture Partnership for Aluminium Production
Country: France
Technology: Carbon Capture
Sector: Aluminium

Fives, a company with over twenty years of experience in decarbonizing industry, has partnered with leading players in the hydrogen sector, digitalization, and research centers to develop carbon capture technologies for the aluminium industry. In collaboration with Aluminium Dunkerque, Trimet, and Rio Tinto, the project focuses on capturing CO_2 directly from the electrolysis pots during aluminium production, a method still in the research stage for this sector. The project is supported under France's 2030 decarbonization plan.[42]

This partnership approach is key to the project's success, with the first phase set for 2024-2027 for experimentation and prototype installation. The aim is to reduce emissions by 50% by 2030, with industrial deployment slated to begin in 2028. The technology uses a three-step process: collecting CO_2-laden gases at the emission source, purifying them through an innovative treatment system, and capturing the CO_2 with amine solvents for storage or further use.

[41] Zore, L. (2024). Decarbonisation options for the aluminium industry. Publications Office of the European Union. https://doi.org/10.2760/880, JRC136525
[42] Fives Group. (2023). Fives develops first CO2 capture solutions for the aluminium industry. https://fivesgroup.com/newspress/detail-view/first-co2-capture-solutions-for-the-aluminium-industry [02.12.2024]

2.3. Cement Industry

In 2020, the global cement industry produced a staggering 4.2 billion tons of cement, contributing over 2.5 billion tons of CO_2 emissions.[43] This represents approximately 6-7% of total global anthropogenic emissions. Cement sector emissions can be broadly categorized into two sources: process emissions and energy-related emissions. Process emissions, accounting for around 60% of total emissions, arise from the calcination process in clinker production, where limestone (CaCO3) breaks down into lime (CaO) and CO_2. The remaining emissions come from the combustion of fossil fuels like coal and natural gas, which provide thermal energy for the calciner and kiln.[44]

Decarbonizing the cement industry is a complex but achievable goal, and key roadmaps from industry organizations such as the Global Cement and Concrete Association (GCCA), International Energy Agency (IEA), and European Cement Association (CEMBUREAU) highlight various levers for emission reductions.

Reducing the clinker-to-cement ratio is essential for lowering process emissions, and there is significant potential for fuel-related emission reductions through technology improvements, enhanced thermal efficiency, and the use of alternative fuels. One such alternative fuel with considerable promise is hydrogen. Among the most promising options is the implementation of CCUS technologies, which are projected to play a critical role in achieving net-zero emissions in the cement sector.[45]

2.3.1. H_2 in Cement

Hydrogen-powered rotary kilns are seen as a key technology for achieving substantial emission reductions in the cement industry. Hydrogen, when used as a fuel, offers the advantage of carbon-free combustion, emitting only water vapor as a by-product. Studies have shown that hydrogen can reduce emissions by up to 44% compared to traditional coal-based methods, making it a highly attractive option for regions where fuel supply is heavily dependent on imports.[46]egration.

However, green hydrogen—produced from renewable sources—remains in the early stages of development (TRL 5-6).[47] While promising, its high cost and limited availability present challenges. Furthermore, the regulatory frameworks governing the production, transportation, and storage of green hydrogen are still evolving, which complicates its widespread adoption. Despite these challenges, several European cement plants are experimenting with small-scale green hydrogen integration.

Case Study 5

Project: H_2CEM
Country: Greece
Technology: Hydrogen
Sector: Cement

The H_2CEM project in Greece aims to incorporate green hydrogen in multiple cement plants, potentially reducing CO_2 emissions by 160,000 tons per year—approximately 8% per ton of product.[48]

[43] GCCA. (2022). *Concrete future roadmap.* Global Cement and Concrete Association. https://gccassociation.org/concretefuture/wp-content/uploads/2022/10/GCCA-Concrete-Future-Roadmap-Document-AW-2022.pdf

[44] Monteiro, J., & Roussanaly, S. (2022). CCUS scenarios for the cement industry: Is CO_2 utilization feasible? Journal of CO_2 Utilization, 61, 102015. https://doi.org/10.1016/j.jcou.2022.102015

[45] CEMBUREAU (2022). CEMBUREAU net zero roadmap. https://cembureau.eu/media/ulxj5lyh/cembureau-net-zero-roadmap.pdf

[46] Jibran, J. A., & Mahat, C. (2023, November). Application of green hydrogen for decarbonization of cement manufacturing process: A technical review. Journal of Physics: Conference Series, 2629(1), 012027. IOP Publishing. https://doi.org/10.1088/1742-6596/2629/1/012027

[47] World Economic Forum. (2023). Net-zero industry tracker 2023 – Cement industry net-zero tracker. https://www.weforum.org

[48] ELYSIS. (n.d.). What is ELYSIS? – Carbon-free smelting. https://elysis.com/en/what-is-elysis#carbon-free-smelting

2.3.2. CCUS in Cement

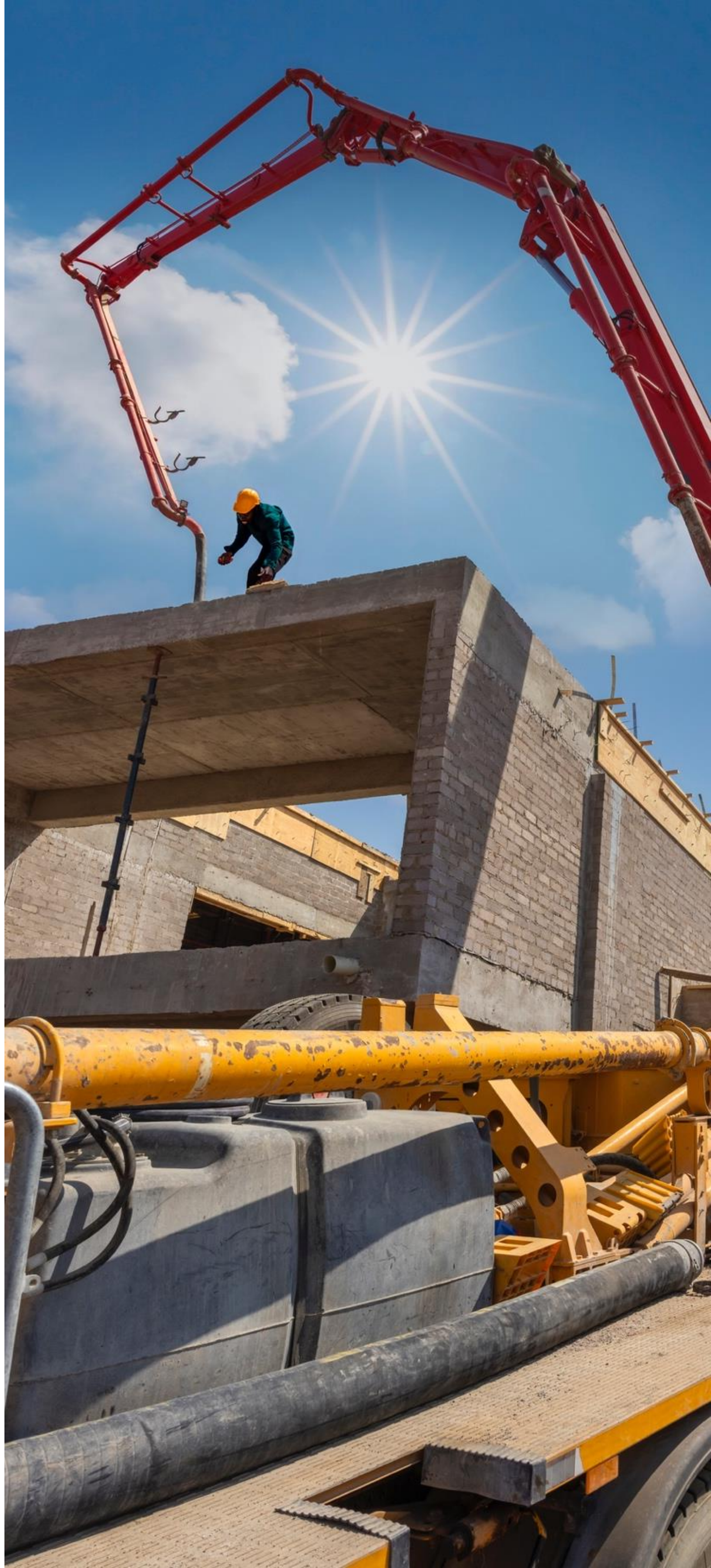
CCUS is another vital tool for reducing emissions in the cement industry, especially given the unique chemistry of the cement production process. This technology, which is currently at a TRL 6-9, has shown significant potential, but its full-scale commercial viability will likely not be realized until after 2030, once infrastructure and regulatory frameworks are better established.[49] At present, however, the high costs of CCUS technologies remain a barrier to their widespread adoption. For instance, if 90% of emissions were captured using CCS technology at a cement plant, the cost of cement production could increase by 65-95%, depending on the specific CO_2 capture technology employed. This highlights the challenge of balancing emission reduction efforts with the economic feasibility of production.[50]

Case Study 6

Project: Edmonton's Lehigh Cement Plan
Country: Canada
Technology: CCUS
Sector: Cement

In an encouraging sign for the sector, Lehigh Cement, a division of Heidelberg Materials, is preparing to launch the world's first full-scale CCUS plant for cement production in 2026. This plant is expected to capture around 1 million tons of CO_2 annually—about 95% of the plant's total emissions. This project signals a significant step toward integrating CCUS at an industrial scale in the cement industry and brings hope for the eventual commercial viability of such technologies.

While the cement sector faces numerous challenges in reducing its emissions, the ongoing efforts by industry leaders and the development of breakthrough technologies offer promising pathways toward carbon neutrality. As CCUS and hydrogen technologies evolve and become more economically viable, the cement industry could play a pivotal role in the transition to a low-carbon future.[51]



[49] World Economic Forum. (2023). Net-zero industry tracker 2023: Cement industry net-zero tracker. https://www.weforum.org/publications/net-zero-industry-tracker-2023/in-full/cement-industry-net-zero-tracker/

[50] Subraveti, S. G., Rodríguez Angel, E., Ramírez, A., & Roussanaly, S. (2023). Is carbon capture and storage (CCS) really so expensive? An analysis of cascading costs and CO2 emissions reduction of industrial CCS implementation on the construction of a bridge. Environmental Science & Technology, 57(6), 2595-2601.

[51] Johnson L. (2023). Carbon capture testing begins at Edmonton cement plant aiming to be first to carbon neutral. Edmonton Journal. Postmedia Network Inc. https://edmontonjournal.com/news/alberta-environment-minister-schulz-starts-ccus-project-at-edmonton-plant [02.12.2024]

2.4. Petrochemical Industry

The petrochemical industry is a key player in the global economy, producing essential materials for sectors ranging from plastics and fertilizers to pharmaceuticals and textiles. However, it is also one of the most challenging sectors to decarbonize. The production of petrochemicals and their derivatives consumes approximately 14% of the world's oil and 8% of global natural gas, contributing significantly to global industrial CO_2 emissions—accounting for around 18% of the total. These emissions stem from a combination of direct process emissions, indirect emissions from energy consumption, and emissions from the end-of-life treatment of petrochemical products.[52]

The petrochemical sector faces several hurdles in reducing its carbon footprint. One of the biggest challenges is its significant reliance on hydrogen, both as a chemical feedstock and a fuel. Hydrogen is used extensively in refining and fertilizer production—together these industries account for more than 85% of global hydrogen consumption. While hydrogen can be a key enabler of decarbonization, it presents both opportunities and obstacles.

2.4.1. H_2 in Petrochemical

On one hand, hydrogen has the potential to replace part of the natural gas used in furnaces, through mixtures of hydrogen and natural gas. However, the use of hydrogen as a fuel depends on infrastructure availability and the efficiency of its production, storage, and distribution. Currently, renewable hydrogen combustion in furnaces is still in the development phase. As a result, hydrogen is seen more as a transitional technology, bridging the gap to fully electrified processes in the future.[53]

2.4.2. CCUS in Petrochemical

In addition to hydrogen, CCUS technologies are vital for decarbonizing the petrochemical industry. These technologies offer significant potential, particularly because it is more economical to capture CO_2 from sources with high concentrations of the gas. In the petrochemical sector, CCUS can play an essential role, especially when applied to high-emission manufacturing processes like ammonia production. These technologies are already being integrated into various projects around the world. This presents a promising opportunity for the industry to close the carbon loop. However, widespread adoption is still evolving, and its implementation at a global scale remains a key challenge.[54]

Case Study 7

Project: Antwerp@C
Country: Belgium
Technology: CCUS
Sector: Energy and Petrochemical

One notable initiative is the Antwerp@C project, which is being developed in the Port of Antwerp, one of Europe's largest industrial clusters. Leading petrochemical companies including BASF, Borealis, ExxonMobil, INEOS, and Total are collaborating on this project to assess the technical and economic feasibility of building CO_2 infrastructure that can support future CCUS applications. The goal is ambitious: to reduce the Port of Antwerp's emissions, which totaled 18.65 million tons of greenhouse gases in 2017, by 50% by 2030. This project underscores the growing commitment of the petrochemical industry to decarbonize, highlighting both the technological potential and the economic challenges of such initiatives.[55]

[52] Jennings, E. T., Hamlin, P. J., Hamlin, C., & Cullen, J. M. (2024). Connected, complex, and carbonized: The country archetypes of the petrochemicals sector. Energy Research & Social Science, 118, 103826. https://doi.org/10.1016/j.erss.2024.103826
[53] Petrochemistry Europe. (2021). Clean hydrogen can contribute to reduce our industry's carbon footprint. Petrochemistry Europe. https://www.petrochemistry.eu/mediaroom/hydrogen-can-contribute-to-petrochemical-industrys-energy-transition-in-europe/
[54] Bauer, F., Kulionis, V., Oberschelp, C., Pfister, S., Tilsted, J. P., Finkill, G. D., & Fjäll, S. (2022). Petrochemicals and climate change: Tracing globally growing emissions and key blind spots in a fossil-based industry (IMES/EESS Report No. 126). Lund University.
[55] Petrochemicals Europe. (n.d.). Europe's petrochemicals industry initiatives to decarbonize & deliver on EU Green Deal. https//www.petrochemistry.eu/mediaroom/europes-petrochemicals-industry-initiatives-to-decarbonize-deliver-on-eu-green-deal/

2.5. Heavy Transport Industry

The transport sector plays a significant role in global carbon dioxide (CO_2) emissions, with road transport accounting for nearly two-thirds of the total. In 2022, heavy transport vehicles were major contributors, emitting substantial CO_2 amounts: buses (452 Mt), medium-duty trucks (631 Mt), and heavy-duty trucks (1,199 Mt). Additionally, most heavy transport vehicles today rely on diesel engines, which not only emit high levels of CO_2 but also harmful pollutants such as particulates and nitrogen oxides, contributing to chronic health issues and premature deaths. This highlights the urgency of decarbonizing the sector.[56]

Decarbonizing heavy transport requires a multi-faceted approach, with cleaner fuel sources being the most prominent solution. Technological advances in the sector have led to expectations that between 29% and 81% of the global heavy-duty transportation fleet will be electrified by 2050. As a result, the sales and adoption of electric buses and trucks are steadily rising, particularly in regions like China and Europe.[57]

2.5.1. H_2 in Heavy Transport

Hydrogen is considered a promising solution particularly for heavy commercial vehicles that frequently travel long distances.[58] Hydrogen-powered vehicles include **Fuel Cell Electric Trucks (FCETs),** which use hydrogen to generate electricity that powers electric motors, and **Battery Electric Trucks (BETs),** which rely on electricity stored in batteries. FCETs offer advantages over BETs, including shorter refueling times and longer ranges, making them particularly suitable for long-haul transport.

However, the use of hydrogen in heavy transport faces several challenges, particularly economic barriers. Establishing hydrogen refueling infrastructure (HRS) is expensive, with each compressor costing between $1 million and $1.5 million. Additionally, high-pressure hydrogen storage systems are a significant cost factor. GH_2, which is produced using renewable energy, is also costly. While the price gap is expected to narrow by the 2040s, blue hydrogen—produced using natural gas with carbon capture—is seen as a more economical option in the short term.[59]

Case Study 8

Project: H_2Haul Project
Country: Europe
Technology: Hydrogen
Sector: Transportation and Logistics

Despite the economic challenges, important initiatives are underway in Europe to advance the use of hydrogen fuel cell trucks. For example, the H_2Haul project, a collaboration with IVECO and VDL, aims to develop and test 16 hydrogen fuel cell trucks to support Europe's zero-emission targets.[60] This project also focuses on establishing the necessary hydrogen refueling infrastructure. Another major initiative, H_2Accelerate TRUCKS, involves partners such as Daimler AG, IVECO, and VOLVO, and aims to deploy 150 hydrogen fuel cell trucks across 9 European countries by 2029.[61]

2.5.2. CCUS in Heavy Transport

In addition to hydrogen and electrification, CCUS technology can play a critical role in decarbonizing long-distance transport. CCUS can be used to capture CO_2 from industrial processes and convert it into synthetic hydrocarbon fuels such as diesel, gasoline, and kerosene. These synthetic fuels, produced using captured CO_2, have lower life-cycle emissions compared to conventional fossil fuels. As regulations around CO_2 emissions become more stringent, the use of CCUS will become increasingly important, with CO_2 feedstocks derived from biomass or DAC being essential for creating these low-emission synthetic fuels.[62]

[56] International Energy Agency (IEA). (n.d.). Trucks and buses. https://www.iea.org/energy-system/transport/trucks-and-buses
[57] International Council on Clean Transportation (ICCT). (n.d.). Heavy vehicles. https://theicct.org/sector/heavy-vehicles/
[58] Verband der Automobilindustrie (VDA). (n.d.). Electromobility using hydrogen. https://www.vda.de/en/topics/electromobility/electromobility-using-hydrogen
[59] International Council on Clean Transportation (ICCT). (n.d.). Heavy vehicles. https://theicct.org/sector/heavy-vehicles/
[60] CORDIS. (n.d.). Hydrogen for heavy-duty vehicles (H2Accelerate). https://cordis.europa.eu/project/id/826236
[61] H2Accelerate. (n.d.). Trucks. Retrieved from https://h2accelerate.eu/trucks/
[62] International Energy Agency (IEA). (2023). CCUS in clean energy transitions: CCUS in the transition to net-zero emissions. https://www.iea.org/reports/ccus-in-clean-energy-transitions/ccus-in-the-transition-to-net-zero-emissions

2.6. Aviation

Aviation is a significant contributor to global CO_2 emissions, responsible for approximately 2.5% of global energy-related CO_2 emissions.[63] Aviation is considered a "hard-to-abate" sector where electrification isn't feasible. The Committee on Climate Change's 2020 report noted that aviation will likely still produce significant emissions by 2050, with any remaining emissions needing to be offset.

The sector's emissions have been growing at a faster rate compared to rail, road, or shipping in recent years. This growth has been particularly noticeable following the pandemic. In 2019, aviation emissions from fossil fuel combustion reached 1,000 Mt CO_2. However, due to pandemic-related travel restrictions, emissions dropped to less than 600 Mt CO_2 in 2020. As demand for air travel surged again, emissions climbed back up to nearly 950 Mt CO_2 in 2023 with the only exceptions being China (due to the Zero Covid Policy) and Russia (because of the ongoing Russia-Ukraine war).[64]

2.6.1. H_2 in Aviation

Key challenges for hydrogen adoption in aviation include propulsion technology and infrastructure. The decarbonization of aviation largely hinges on the development and widespread adoption of **Sustainable Aviation Fuels (SAFs).** SAFs come in two main forms:

1. **Synthetic biofuels,** which are derived from organic materials. However, their supply is limited.
2. **E-fuels,** which are produced by combining hydrogen with carbon dioxide (CO_2).

Airbus has highlighted the potential scalability of **hydrogen-based synthetic fuels,** noting that they could significantly reduce production costs. This makes them an attractive option for long-term decarbonization, as they can be used with existing infrastructure and engines, making them more easily adoptable across the industry.

Meanwhile, **Boeing** has emphasized SAF's potential to **reduce carbon emissions** in aviation over the next **20 to 30 years.** They see SAF as an essential bridge in the transition to cleaner aviation fuels. In 2022, a notable milestone occurred when the **Royal Air Force (RAF)** successfully completed a **90-minute flight using 100% SAF,** showcasing the viability of SAF in operational flights.[65]

2.6.2. CCUS in Aviation

CCUS mainly supports aviation decarbonization through carbon offsetting and synthetic jet fuel production. Point-source carbon capture provides CO_2 for e-fuel production, while Direct Air Capture (DAC) has broader potential to address the sector's emissions. However, DAC is currently expensive, costing between USD 600-1,000 per metric ton of CO_2, compared to $15-130 for point-source capture. DAC costs are expected to decrease over time.

Case Study 9

Project: Climeworks / Heirloom / Carbon Engineering
Country: Iceland, Switzerland, USA, Canada
Technology: CCUS / Direct Air Capture
Sector: Aviation

Companies like Climeworks (Switzerland), Heirloom Carbon Technologies (USA), and Carbon Engineering (Canada) are advancing this technology. Climeworks' facility in Iceland captures 4,000 tons of CO_2 annually, Heirloom's plant in California captures 1,000 tons, and Carbon Engineering's upcoming plant in Canada is expected to capture 500,000 tons per year. These projects could significantly contribute to aviation decarbonization, especially through e-fuel production.[66]

[63] International Energy Agency. (n.d.). *Aviation.* https://www.iea.org/energy-system/transport/aviation
[64] Ibid.
[65] UK Parliament. (2023). Developing a sustainable aviation sector: UK Government response to the committee's third report of session 2022–23. https://committees.parliament.uk/publications/33292/documents/180198/default/
[66] Clean Air Task Force. (2024). Decarbonizing aviation: Enabling technologies for a net-zero future.

3 **Future Outlook:** Technological Trends, Costs, and Adoption Potential

3.1. Hydrogen and CCUS Cost Reductions

The transition to a low-carbon economy heavily relies on the development of both H_2 and CCUS technologies. While each of these solutions presents significant potential, they are intrinsically linked, particularly in their role in decarbonizing hard-to-abate sectors such as heavy industry, transportation, and energy generation. Technological advancements and the development of cost reduction strategies for these technologies will be crucial for their widespread adoption.

For **green hydrogen,** cost reductions are driven by advancements in electrolyzer technology, particularly through scaling up production and optimizing system designs. Increasing the size of electrolysis plants from 1 MW (common in 2020) to 20 MW could lead to cost reductions of over 30%. Furthermore, automated processes in large-scale, gigawatt-level manufacturing facilities can significantly drive down costs through economies of scale. However, challenges remain, such as the limited availability of materials used in electrolyzers, which could constrain scaling efforts. Additionally, efficiency losses at low load power supply impact the flexibility of electrolysis systems, further complicating the economic viability of large-scale green hydrogen production.[67]

Despite these hurdles, the potential for further cost reduction exists through **learning rates**—a concept derived from the historical declines seen in technologies like solar photovoltaics. The learning rates for electrolysers are expected to range between 16% and 21% as production capacity increases, making green hydrogen increasingly cost-competitive as these technologies mature.[68]

For **blue hydrogen,** one potential solution to the cost challenge of hydrogen production is integrating carbon capture directly within the gas reforming process. By capturing CO_2 from the reforming unit itself, this streamlined method eliminates several intermediate steps, resulting in lower production costs for blue hydrogen. The captured CO_2 can either be stored in carbon capture facilities or repurposed for use in industries that require high-quality CO_2.[69]

In the short term, blue hydrogen is likely to remain the more cost-effective option to meet the growing demand for low-carbon hydrogen. The transition to green hydrogen will gradually occur as technological advancements continue and as natural gas supplies diminish. Both green and blue hydrogen will need to evolve in parallel to facilitate a smoother transition toward a fully decarbonized hydrogen economy.[70]

In parallel, **CCUS** is essential for decarbonizing industries and applications that are otherwise difficult to electrify or decarbonize using alternative technologies. The **IEA** highlights the potential for CCUS to capture emissions from power and industrial plants, preventing up to 8 billion tonnes of CO_2 annually by 2050—around 25% of today's energy-sector emissions. CCUS plays a critical role in carbon removal when paired with bioenergy or direct air capture technologies, further contributing to achieving global net-zero goals.[71]

However, the costs associated with CCUS vary significantly. Capturing CO_2 from highly concentrated sources, such as ethanol production or natural gas processing, can cost between **USD 15-25 per tonne of CO_2.** For more dilute sources like cement production or power generation, the cost rises to **USD 40-120 per tonne of CO_2.** Although **direct air capture,** which removes CO_2 from the atmosphere, is currently the most expensive, it is still an essential tool for long-term emissions reduction and balancing emissions that are otherwise unavoidable. While other technologies, such as renewable energy generation and battery storage, have experienced substantial cost declines over the past decade, carbon capture technologies have not seen comparable reductions. In fact, the costs associated with carbon capture have remained largely stagnant, posing a major barrier to widespread adoption.[72]

67 International Renewable Energy Agency (IRENA). (2020). Green hydrogen cost reduction. https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction
68 Ibid.
69 UK Parliament. (2023). Publications and documents: 33292. https://committees.parliament.uk/publications/33292/documents/180198/default/
70 Ibid.
71 International Energy Agency (IEA). (2023, February 28). Is carbon capture too expensive? Retrieved from https://www.iea.org/commentaries/is-carbon-capture-too-expensive
72 Ibid.

3.2. Technology Adoption

Given the diverse process requirements and emission sources across different industries, it is unlikely that a single technology will dominate the transition to decarbonization. CCUS and hydrogen technologies currently span a wide range of Technology Readiness Levels (TRLs). At lower TRLs, the focus is on proving the feasibility of these technologies, while higher TRLs focus on ensuring commercial viability.[73]

One of the key uncertainties is the long-term effectiveness and safety of geologically storing captured carbon dioxide. The unique nature and scale of CCUS projects—driven by the amount of CO_2 captured, stored, or utilized in each sector—limits technological learning and hinders significant cost reductions.[74] For CCUS, technologies range from early-stage research (TRL 1-3) to fully operational, large-scale systems in commercial service (TRL 8-9). At TRL 6-7, CCUS technologies are in advanced stages of development and demonstration, with pilot and sub-scale prototypes being tested in real-world environments.

Hydrogen technologies also follow a similar path, with green hydrogen electrolyzers and blue hydrogen systems progressing through early-stage research, development, and demonstration phases. As of now, many hydrogen technologies are in the development stage, with increasing commercial deployment expected as they advance to higher TRLs.[75]

The choice of clean fuel will largely depend on local supply chains, cost considerations, and the specific demands of each sector. Achieving cost reductions in key decarbonization technologies will require substantial government investment. This support is critical to fund large-scale research and development efforts, infrastructure networks, as well as pilot projects, which will help accelerate innovation and bring these technologies to market at competitive prices.[76]

[73] Global CCS Institute. (2021). Technology readiness and costs for CCS. https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf
[74] Institute for Energy Economics and Financial Analysis (IEEFA). (2023). CCUS will not play a major role in steel decarbonisation. https://ieefa.org/articles/ccus-will-not-play-major-role-steel-decarbonisation
[75] Global CCS Institute. (2021). Technology readiness and costs for CCS. https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf
[76] BloombergNEF. (2020). BNEF sector coupling report. https://data.bloomberglp.com/professional/sites/24/BNEFSector-Coupling-Report-Feb-2020.pdf

4 Accelerating Adoption of CCUS and Hydrogen

4.1. Invesments and Governance

The widespread adoption for the **CCUS and hydrogen**-based technologies faces several significant challenges. While the fundamental technologies behind CCUS and hydrogen are well-understood, scaling them remains unproven, and the policy frameworks supporting its deployment are still evolving. To drive large-scale adoption, these policies must incorporate a mix of incentives, regulatory approvals, and risk management strategies. However, the current policy landscape remains uncertain and inconsistent, making it difficult to create a clear path forward for investors and developers.

Policymakers need to carefully determine how to prioritize clean technologies and create effective policies for its low-carbon production and use. This will be crucial for developing a successful strategy to achieve rapid and widespread decarbonization across the economy. Robust government financial support and targeted incentives are also crucial for accelerating the deployment of CCUS and hydrogen technologies. These mechanisms will help overcome the initial cost barriers and stimulate long-term investment in these emerging sectors.

While some governments prioritize renewable electricity in their decarbonization strategies, others, such as Australia, Canada, China, Japan, South Korea, the Netherlands, Norway, and the United States, advocate for a broader technology portfolio that includes hydrogen produced from fossil fuels combined with CCS. However, these strategies often lack a comprehensive analysis of the emissions impact of CCS in real-world conditions. If CCS is not implemented in parallel with the development of new fossil fuel-based hydrogen supply chains, there is a risk of significant emissions during the startup phase, undermining the effectiveness of these technologies in meeting long-term decarbonization goals.[77]

A major barrier is the lack of established revenue streams for **CCUS**, which makes it challenging to attract private investment. Most CCUS projects rely heavily on government support, but scaling the technology to the necessary level will require financial resources beyond what governments can realistically provide. These projects are typically large and complex, with many past initiatives facing delays or even cancellations. Successful implementation for new advancementes requires coordinated development across multiple stages which demands collaboration among a wide range of stakeholders, each with differing goals and timelines. Additionally, public perception continues to be a challenge. While they are essential for decarbonization, it is often viewed as a means of prolonging fossil fuel use, leading to resistance and complicating efforts to secure public funding or subsidies for such projects.[78]

[77] ScienceDirect. (2021). Article: Impact of carbon capture and storage on energy systems. Energy Policy, 149, 1121–1132. https://doi.org/10.1016/j.enpol.2021.1121. https://www.sciencedirect.com/science/article/abs/pii/S0306261921014215

[78] Open Research Europe. (2023). Research on green hydrogen and carbon capture technologies. Open Research Europe, 3, Article 205. https://doi.org/10.12688/open-research-europe.3.205. https://open-research-europe.ec.europa.eu/articles/3-205

Additionally, the current carbon accounting systems provide little incentive for **hydrogen** importers—such as Japan and South Korea—to prioritize "zero-emissions" hydrogen or demand high carbon capture rates from exporting countries. Emissions from hydrogen production are often attributed to the exporting nations, which may focus more on establishing hydrogen export industries than on reducing their own national emissions. This is similar to the situation with liquefied natural gas (LNG) exports, where emissions are frequently counted as part of the exporter's footprint rather than the importer's.[79]

Governments must take more decisive action to stimulate demand for low-emissions hydrogen. While policies such as quotas, mandates, and carbon contracts for difference have been introduced, their impact remains limited in both scope and reach. To accelerate green hydrogen demand, governments should target sectors that already utilize hydrogen or hold significant potential for its adoption, such as steel, shipping, and aviation. These industries are often concentrated in industrial hubs, and by pooling demand in these areas, governments can help create economies of scale, thus reducing risks for hydrogen producers. Additionally, leveraging public procurement to purchase products made with low-emissions hydrogen, and fostering markets where consumers are willing to pay a premium for such products, can encourage early adoption and stimulate further demand.[80]

Besides the national incentives, international collaboration and the development of standardized protocols are essential for creating a global framework that supports the widespread adoption of **CCUS and hydrogen** technologies. Inconsistent regulations represent a significant challenge for the industries, as the regulatory framework varies greatly across countries and regions. This lack of standardization complicates efforts to design systems that can be universally applied. However, governments are beginning to create hydrogen roadmaps and introduce incentives to support the development of hydrogen technologies. As the low-carbon economy continues to grow, it is expected that more uniform and streamlined regulations will emerge, helping to drive innovation and facilitate the global adoption of the new solutions.[81]

[79] ScienceDirect. (2021). Impact of carbon capture and storage on energy systems. Energy Policy, 149, 1121–1132. https://doi.org/10.1016/j.enpol.2021.1121. https://www.sciencedirect.com/science/article/abs/pii/S0306261921014215

[80] International Energy Agency (IEA). (2024). Global hydrogen review 2024: Executive summary. https://www.iea.org/reports/global-hydrogen-review-2024/executive-summary

[81] International Renewable Energy Agency (IRENA). (2024, July). Green hydrogen strategy design. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Jul/IRENA_Green_hydrogen_strategy_design_2024.pdf

4.2. Research and Development

Research and development is essential for the successful adoption of low-carbon technologies like hydrogen, as it drives innovation and helps overcome the technical barriers that hinder large-scale deployment. In particular, advancements in storage, production, and infrastructure are crucial for making hydrogen a viable alternative to conventional energy sources. With ongoing research, breakthroughs in these areas could significantly reduce costs and improve efficiency.

For example, the challenge for green hydrogen is its high production cost. Even though it is a more environmentally friendly option, it remains more expensive than conventional energy sources. Its low energy density and high flammability introduce further complexities for its widespread adoption and use on a large scale.[82] To overcome these obstacles, engineers are investigating various hydrogen storage methods, including compressed gas, liquid hydrogen, and solid-state storage. Each of these approaches has its own trade-offs.

Compressed gas storage requires heavy, high-pressure tanks, while liquid hydrogen needs to be kept at costly cryogenic temperatures. Emerging materials such as carbon nanotubes and metal-organic frameworks (MOFs) offer promising solutions for more efficient storage. These materials could allow hydrogen to be stored at lower pressures and higher densities, reducing both storage costs and energy consumption.[83]

The adoption of CCUS and hydrogen technologies is essential for achieving global decarbonization goals, with countries taking unique approaches to advance innovation. China is rapidly advancing in green hydrogen R&D and deployment, particularly in electrolysis and fuel cells. The USA emphasizes advanced electrolysis and storage solutions through significant investments, while the EU focuses on integrating electrolysis with renewable energy. Japan prioritizes innovative approaches to hydrogen storage and production to secure energy stability.

Efforts are focused on reducing CO_2 capture costs, improving separation materials, and integrating these technologies into industrial processes. Countries like the USA and EU invest heavily in CCUS pilot projects, while China scales industrial applications, and Japan explores carbon recycling innovations.[84]

International collaboration plays a pivotal role in accelerating these technologies. Programs like Mission Innovation and the IEA foster shared knowledge and risk reduction, enabling countries to advance hydrogen and CCUS technologies effectively. By aligning R&D, infrastructure, and policy support, these efforts are driving a global transition to a low-carbon economy.[85]

[82] Horizon Educational. (n.d.). The 10 biggest challenges engineers face with hydrogen and how to solve them. https://www.horizoneducational.com/the-10-biggest-challenges-engineers-face-with-hydrogen-and-how-to-solve-them/t1620?currency=usd
[83] Ibid.
[84] ScienceDirect. (2024). [Title of the article]. International Journal of Hydrogen Energy. https://www.sciencedirect.com/science/article/pii/S0360319924014150
[85] International Energy Agency. (n.d.). CCUS in clean energy transitions: Accelerating deployment. https://www.iea.org/reports/ccus-in-clean-energy-transitions/accelerating-deployment

4.3. Infrastructure and Collaboration

For the wide adoption of **CCUS**, leveraging existing geological storage sites and establishing CCUS clusters are crucial for accelerating large-scale CO_2 capture and ensuring effective long-term storage solutions for captured emissions. These clusters bring together emission-intensive facilities, such as industrial plants and power plants, to form a capture network that connects to large-scale CO_2 storage sites via shared transport infrastructure. This shared infrastructure reduces costs and increases efficiency by allowing multiple emitters to utilize it. The anchor projects, typically large CO_2 emitters like thermal power plants or industrial facilities, help cover initial infrastructure costs, making it more affordable for others to join the cluster. CCUS clusters can also span multiple geological sequestration sites, including oil fields for enhanced oil recovery or CO_2 utilization projects. However, the high initial mobilization and infrastructure costs make early-stage CCUS cluster projects financially challenging. Long-term, low-cost financing, often supported by government and international clean energy funds, is crucial to overcoming these economic barriers.[86]

Similarly, H_2 deployment requires the transportation of large volumes of hydrogen from production sites to facilities across various geographic locations. Repurposing existing natural gas pipelines for hydrogen transport presents a promising solution. By adapting current pipeline systems, significant savings can be realized in both construction costs and time, reducing the need for building entirely new networks. This approach not only supports the early rollout of hydrogen infrastructure but also offers a flexible and scalable pathway to integrate hydrogen into existing energy systems. However, retrofitting these systems is still costly and time-consuming. Moreover, many hydrogen technologies, such as fuel cells and turbines, are still under development and are not yet as efficient or cost-effective as conventional systems, which hinders their adoption. However, engineers are making strides in developing advanced fuel cells and exploring ways to blend hydrogen with natural gas in existing pipelines, aiming to ease the transition and reduce costs.[87]

The following case studies illustrate various efforts and strategies employed by different regions to repurpose natural gas pipelines for hydrogen transport, highlighting the potential of this solution in the transition to a low-carbon economy.

Case Study 10

Project: Netherlands National Hydrogen Backbone
Country: Netherlands
Technology: Adaptation of existing natural gas pipelines
Sector: Heavy Industry

In the Netherlands, the government, through its gas transmission system operator, plans to invest approximately €1.5 billion to establish a hydrogen backbone by 2030, with 50% of the funding provided through government grants. The project will involve constructing 200 km of new pipelines, while a significant portion of the investment will be dedicated to adapting existing natural gas infrastructure to accommodate hydrogen.

[86] National Institution for Transforming India (NITI Aayog). (2022, December). CCUS report. https://www.niti.gov.in/sites/default/files/2022-12/CCUS-Report.pdf
[87] Horizon Educational. (n.d.). The 10 biggest challenges engineers face with hydrogen and how to solve them. https://www.horizoneducational.com/the-10-biggest-challenges-engineers-face-with-hydrogen-and-how-to-solve-them/t1620?currency=usd

Case Study 11

Project: National Hydrogen Strategy
Country: Germany
Technology: Hydrogen transport infrastructure, production, storage and distribution
Sector: Industrial and Transport

Germany's revised National Hydrogen Strategy, announced in July 2023, outlines plans for an 11,200 km hydrogen backbone by 2032. The first phase of this grid, comprising 1,800 km, is expected to receive partial funding from European resources by 2028. This initial phase will also be supported by Germany's private, regionally owned companies, with government incentives such as contracts for difference helping to drive development.

A critical challenge for hydrogen sector is the absence of clear regulatory frameworks, which creates uncertainty around funding. In the absence of enforceable regulations, gas operators may rely on private or state subsidies. Although major investments in hydrogen infrastructure are not expected before 2030, it is essential for the sector to begin preparing financially for future growth. Strong financial policies and regulatory support will be crucial for cost recovery and the overall success of these projects, as regulatory changes could introduce further uncertainty.[88]

[88] S&P Global. (n.d.). Hydrogen: New ambitions and challenges. https://www.spglobal.com/en/research-insights/special-reports/look-forward/hydrogen-new-ambitions-and-challenges

5 Concluding Remarks

The global transition to a **low-carbon economy** is increasingly reliant on the rapid and scalable deployment of **hydrogen** and **CCUS** technologies. These solutions are not simply complementary; they are **fundamental** for addressing the unique challenges of hard-to-decarbonize sectors, such as heavy industry and transportation, where electrification alone falls short. As the world works toward net-zero emissions, the symbiosis between hydrogen and CCUS will be pivotal in shaping the future of **industrial decarbonization, energy security,** and **sustainable growth**.[89]

Investors who enter early into this domain gain a **strong position** in two of the most important, rapidly growing markets of the future: **clean energy technologies** (like hydrogen) and **carbon management** (through CCUS). Both sectors are projected to expand exponentially in the coming decades as governments around the world push for net-zero emissions targets and industries seek decarbonization solutions. By positioning themselves early in these sectors, investors can capture significant market share and establish themselves as leaders in these transformative fields.

Governments, too, play a crucial role by supporting these technologies. Through **policies, financial incentives,** and **regulatory frameworks,** they can create a favorable environment for investment, encouraging private capital to flow into the development of **sustainable technologies.**

By backing projects that align with their environmental and economic goals, governments help to accelerate the **transition to a low-carbon economy** while stimulating job creation, technological innovation, and international collaboration.

Ultimately, both **investors** and **governments** have a shared interest in **driving the transition** to a **sustainable future**. By collectively supporting technologies that reduce emissions and increase energy efficiency, they help ensure the global economy is better prepared for future challenges, such as climate change, energy security, and resource scarcity. As these technologies gain traction, they not only foster environmental sustainability but also present new opportunities for growth and leadership in a rapidly evolving global market.[90]

The **synergy** will be crucial for decarbonizing the most challenging sectors. Together, these technologies have the potential to transform hard-to-abate sectors into low-carbon powerhouses, driving the world toward a sustainable, net-zero future. Although the journey will demand sustained collaboration, technological innovation, and significant investment, high production costs, limited refueling infrastructure, and the early stage of these technologies can be overcome through **continued innovation, policy support,** and **global partnerships.** Ultimately, the success of regional hydrogen hubs, CCUS clusters, and international collaborations will be critical in driving down costs, accelerating adoption, and ensuring the global transition to a sustainable, low-carbon economy.

In the next few decades the convergence of **cost-competitive green hydrogen, scalable CCUS infrastructure,** and **supportive policies** could unlock the decarbonization of hard-to-abate sectors and propel the world toward net-zero emissions. While the path forward presents challenges, the collaboration of governments, industries, and innovators—coupled with the financial and technological momentum—will ensure that a **sustainable, decarbonized global economy** is not just a vision, but a reality within reach.

[89] World Economic Forum (WEF). (2023). Transitioning industrial clusters towards net zero. https://www3.weforum.org/docs/WEF_Transitioning_Industrial_Clusters_towards_Net_Zero_2023.pdf
[90] International Energy Agency (IEA). (2023). How governments support clean energy start-ups: Financing. https://www.iea.org/reports/how-governments-support-clean-energy-start-ups/financing

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