CAETS Report

TOWARDS LOW-GHG EMISSIONS FROM ENERGY USE IN SELECTED SECTORS: LOOKING BEYOND 2040

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on behalf of CAETS Energy Community

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Acknowledgements

This report is based on the work of 52 members of the project's working groups from 24 countries, thereby mirroring the international nature of CAETS. Their names and country affiliations are listed in the Project leads and working groups section of the report.

The working groups functioned under the guidance of CAETS Energy Community Leads Axel Meisen, Yves Bamberger and Neven Duić. They were ably assisted by Christopher Frantz (Senior Project Manager at the Canadian Academy of Engineering, CAE), Alison Larabie Chase (Manuscript Editor), and Abigail Dempster (Co-op Student, CAE). Without their skillful contributions, this work and report would not have been possible.

Since the report is future-oriented and the future is uncertain, readers are encouraged to consider the issues, rationale and implications presented in the report and draw their own conclusions. These conclusions will naturally differ by country and region.

We are grateful for the input and feedback on an earlier draft of this report provided by the following 14 internal and 16 external reviewers:

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Internal reviewer: Snow Barlow, Australia
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Agriculture and Food Industry
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External reviewers: John MacArthur, U.K.; Raj Shah, U.S.A.

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Cement Industry
Internal reviewer: Rita Hofmann, Switzerland

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Iron and Steel Industry
Internal reviewer: Frank Behrendt, Germany
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External reviewer: Andreas Athienitis, Canada

Coupling
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All reviewer comments were carefully evaluated and appropriate changes were made.

In accordance with CAETS procedures, the revised text was submitted to CAETS Member Academies for consideration and endorsement. This process led to some refinement in wording and the inclusion of several additional references and a glossary.

All contributions are gratefully acknowledged, together with the financial support provided by the Canadian Academy of Engineering and CAETS.

The views expressed in this draft report can in no way be taken to reflect the official opinion of the CAE or any of the CAETS Member Academies.

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Project Leads and Report Editors

Executive summary

In 2022, CAETS issued a major report, *Towards low-GHG emissions from energy use in selected sectors*. That report, which focused on seven major industry sectors, identified emissions and emission reduction initiatives that are currently underway and promise to result in large-scale emission reductions by the year 2040.

As the 2022 report was completed, it became clear that additional initiatives were needed to achieve further GHG reductions and that the time horizon should be extended. The CAETS Energy Community therefore initiated a follow-up project, called the Sequel Project, to address the following focal question:

> **What actions need to be taken now, and in the near future, so that sufficient technologies are available and realistically deployable to ensure low GHG emissions from energy use in selected sectors beyond the year 2040?**

The sectors addressed in the Sequel Project are:

- Forestry industry
- Oil & gas industry
- Cement industry
- Buildings and smart cities
- Agriculture & food industry
- Chemical industry
- Iron & steel industry

GHG emissions unrelated to energy use in these sectors were considered as appropriate, and supplementary cross-cutting chapters on hydrogen, carbon capture and storage (CCS), and coupling (i.e., multi-industry integration) are included. These additions provide a more complete view of future decarbonization challenges and opportunities.

Project methodology

The long-term future of GHG emissions relevant to these seven industry sectors is uncertain, shaped by complex interactions that include, but are not restricted to, geopolitics, demographics, policies and regulations, markets, economics and investments, public attitudes, technological advances, and environmental changes. Predicting the outcomes of these interactions with certainty is difficult, if not impossible, yet strategies are needed to prepare for a wide range of possibilities.

The Sequel Project employed the foresight approach with scenario creation to arrive at strategies applicable under a wide range of conditions. This work was performed by 52 experts convened from CAETS Academies, professional organizations, industry and academia, spanning 24 countries. The report also benefitted from contributions by 16 external reviewers and official feedback from several CAETS Academies.

Main results: scenarios and strategies

The scenarios for each industry sector were determined and the following strategies were identified to meet the goal of low GHG emissions beyond 2040:

Forestry industry:	• Enhance forest value and carbon storage • Develop sustainable, circular products • Maximise use of residuals • Ensure availability of expert personnel
Agriculture & food industry:	• Widen understanding of terrestrial ecosystems and the roles of agriculture • Support farmers to mitigate GHG emissions and recycle nutrients, water and energy • Enhance use of digital technologies and AI, and increase international collaboration
Oil & gas industry:	• Explore the use of small modular refineries when special conditions apply • Increase electrification of major process units and use of hydrogen • Prepare for evolving product demands, including from the chemical industry • Continue to reduce emissions • Capitalise on opportunities in the natural gas and liquified natural gas sectors
Hydrogen	• Accelerate, optimise and increase stability of green hydrogen production, especially by means of electrolysis • Develop expertise and expand understanding of the formation and production of geologic hydrogen • Evaluate the viability of and pursue commercial-scale geologic hydrogen production by locating suitable deposits of magnesium–iron silicates followed by stimulation with water or brines
Carbon capture & storage (CCS):	• Rapidly increase current CCS deployment rates, including technology cost reductions • Increase Technology Readiness Levels of CCS process technologies • Use international collaboration to minimise unnecessary duplication efforts

	• Provide clear and stable policies, regulations and incentives
Chemical industry:	• Identify, develop and produce new chemicals that meet sustainability and market criteria (including new plastics and inorganics for electric vehicles), and improve recyclability of final products • Accelerate production of major energy carriers, including NH_3 and H_2 • Develop new catalysts and processes, especially electrochemical processes • Use green hydrogen as a raw material, reducing agent and/or fuel
Cement industry:	• Innovate materials and manufacturing, including advanced chemistries and electrochemical processes, while adapting to changing market demands • Standardise durability and long-term performance assessment approaches and implement policies to incentivise sustainability • Accelerate shift to non-fossil energy sources • Utilise Grand Challenge approaches to accelerate innovation
Iron & steel industry:	• Boost H_2 utilisation in blast furnaces and accelerate alternative H_2-based processes • Electrify key process units (EAF, ESF) to cut carbon intensity • Adapt to new product demands (e.g., COASTALUME, high-Mn TWIP) • Maximise circularity by recycling by-products and scaling next-gen electrolytic processes
Buildings & smart cities:	• Promote active citizen and decision-maker engagement • Adapt to climate change-driven extreme weather impacts (floods, heat, etc.) • Create resilient water and energy systems that are sustainable and affordable • Modernise public and private building stocks
Coupling:	• Increase inter-industry coupling and coordination

- Improve policies, social acceptance and education regarding coupling
- Scale up known technologies and electrify sectors

A separate paper will be published on the ICT & data centres sector. Changes in this sector are occurring so rapidly that an assessment using the foresight approach with a time horizon beyond the year 2040 was deemed to be impractical.

The following overarching strategies (called "robust strategies"), which can be adopted by all sectors and are applicable to all scenarios, were identified:

- Ensuring a well-educated, knowledgeable citizenry that will support the introduction and use of policies, products and processes aimed at meeting sustainability objectives.
- Maintaining and expanding an expert workforce capable of conceptualising and implementing new products and processes. This will require stronger and better-resourced educational institutions and research centres of excellence and heightened collaboration among industry, academia and government.
- Implementing policies, regulations and practices, including incentives and taxation measures, that are more supportive of accelerated process and product innovation.
- Intensifying collaboration at the national and international levels to accelerate development and adoption of products and processes without prohibitive trade barriers and subsidies.
- Using digitisation and artificial intelligence to create and implement these changes.
- Accounting for regional and national characteristics and differences, levels of general and economic development and the capital-intensive nature of these industry sectors.

Implementing these strategies will be complex and require the expertise and collaborative leadership of CAETS Academies and their members.

Intent and future work

The CAETS Energy Community did not develop this report with the intent of being prescriptive, but rather to engage readers in considerations and actions appropriate for their industry sectors and national realities. As the work neared completion, two additional general conclusions were reached:

- Artificial intelligence tools could be used to gain additional insights into industry characteristics, possible strategies and potentially attainable results. Preliminary indications were promising; however, they also suggested that considerably more work is needed beyond the scope of the Sequel Project to harmonize AI insights with engineering fundamentals and local conditions.

- A greater understanding of energy security is needed, including energy affordability for end users. A new project to support this need has been initiated by the CAETS Energy Community under the leadership of the Indian National Academy of Engineering (INAE).

Introduction

This is a future-oriented report resulting from the work of the CAETS Energy Community. It is intended for decision-makers and senior engineers in private and public organisations concerned with reducing greenhouse gas emissions from major industry sectors. The report is written with an emphasis on fundamentals. Important background information is provided, thereby making the report accessible to members of the public and media.

In 2022, CAETS issued a major report, *Towards low-GHG emissions from energy use in selected sectors*,[1] which identified emissions and emission reduction initiatives that are currently underway and are expected to result in large-scale emission reductions by the year 2040. That report focused on seven industry sectors:

- Food and agriculture
- Oil and gas
- Cement
- Information and communications technologies
- Buildings and smart cities
- Chemicals
- Iron and steel

As the report was being finished, it became clear that additional initiatives were needed to achieve further GHG reductions and that the time horizon should be extended beyond 2040. The CAETS Energy Community therefore initiated the "Sequel Project" to address the following question (subsequently called the focal question):

> **What actions need to be taken now, and in the near future, so that sufficient technologies are available and realistically deployable to ensure low GHG emissions from energy use in selected sectors beyond the year 2040?**

GHG emissions unrelated to energy use in these sectors were also considered. Carbon capture and storage (CCS), hydrogen, and coupling—which refers to energy and material exchanges between sectors—were deemed to be of high long-term importance and were therefore also included in the Sequel Project.

Additionally, the forestry sector was identified as an industry worth addressing in the context of energy-related GHG emissions. While it was previously incorporated into the food and agriculture chapter, the increasing relevance of the forestry sector justified a separate chapter in this report.

Like the 2022 CAETS report, this report only addresses GHG emissions that arise within the sectors. Emissions resulting from external energy sources and the use of the products produced by the sectors are not addressed in this work.

The long-term GHG emissions associated with the aforementioned sectors cannot be predicted quantitatively and with certainty, because they depend on many factors and the interaction of those factors, including engineering advances, policy changes, geopolitical conditions and public attitudes. However, several foresight methodologies are available to address long-term issues under conditions of uncertainty. For the Sequel Project, the scenario creation methodology was chosen. It has been successfully used by public and private sector organisations, and it logically leads to strategies that are applicable to a wide range of future possibilities.[2,3,4]

In essence, the scenario creation method consists of six steps, starting with the focal question and a review of what is known, then proceeding with the identification of the drivers (also called forces and factors) that shape the future, selection of critical uncertainties, and characterisation of four scenarios before arriving at strategies that are suitable for a wide range of scenarios. The method is further described in Appendix 1 (see page 13).

Working groups

Working groups were created for each industry sector and subject area, consisting of experts drawn from CAETS Academies, professional organisations, industry and academia. These experts have wide-ranging expertise and experiences, typically extending beyond their home countries. The working groups were encouraged to reflect geographic, social and technical diversity in their thinking and strategy development.

The membership of the working groups is shown on page 11.

A working group on ICT & Data Centres was also formed with the following membership: Erol Gelenbe, UK (Chair); Yves Bamberger, France; Robert Crawhall, Canada; Tadeusz Czachorski, Poland; Franco Davoli, Italy; Michaela Meo, Italy; and Albert Zomaya, Australia. However, the working group concluded that it could not anticipate energy demands and related GHG emissions for the ICT sector with certainty beyond approximately 2030. Its timeframe therefore did not align with 2040 and beyond. It was therefore decided to publish the group's findings separately from the Sequel report.

The Sequel Project was led by Axel Meisen (Canada), with high-level support from Yves Bamberger (France) and Neven Duić (Croatia). It received valuable administrative and financial support from the Canadian Academy of Engineering.

The working groups met periodically online, starting in the summer of 2023. They exchanged information electronically and also met several times in joint online sessions. The result is the present report.

Draft reports were presented in the 2024 CAETS Conference (Helsinki, Finland, July 1–4, 2024) and the 2025 CAETS Conference (Brisbane, Australia, September 8–11, 2025). Since then, the report has undergone further refinements, and the chapters have been internally and externally reviewed. The resulting report was submitted to the CAETS Academies for their review and endorsement; these reviews provided important comments, leading to changes that are reflected in this final report.

Composition of the Sequel Project working groups

Forestry industry Tom Browne, Canada (Chair) Peter Axegård, Sweden Ludo Diels, Belgium Richard Kerekes, Canada Ian de la Roche, Canada Esa Vakkilainen, Finland	**Agriculture & food industry** Snow Barlow, Australia (Co-Chair) Martin Fraguio, Argentina (Co-Chair) Chris (Hyung-Sool) Lee, Korea
Oil & gas industry Godwin Igwe, Nigeria/USA (Chair) José Luis Aburto, Mexico Vaughan Beck, Australia Manuel Bravo, Spain Erwin Fritz de la Orta, Mexico Henrik Lund Frandsen, Denmark Dirk Smit, Netherlands Joe Zhou, Canada	**Hydrogen** Henrik Lund Frandsen, Denmark (Co-Chair) Dirk Smit, Netherlands (Co-Chair)
Carbon capture & storage (CCS) Vaughan Beck, Australia (Chair)	**Chemical industry** Oscar Vignart, Argentina (Co-Chair) Frank Behrendt, Germany (Co-Chair) Tony Bi, Canada Funmi Coker, Nigeria Henrik Lund Frandsen, Denmark Rita Hofmann, Switzerland Hyunjoo Lee, Korea Chinho Park, Korea
Cement industry Kimberly E. Kurtis, USA (Co-Chair) Rui Cai, China (Co-Chair) Neven Duić, Croatia Ravindra Gettu, India R. Douglas Hooton, Canada Wang Lan, China Paulo J.M. Monteiro, USA/Brazil	**Iron & steel industry** Il Sohn, Korea (Co-Chair) Karl Buttiens, Belgium (Co-Chair) Xinping Mao, China (Co-Chair) Eloy Álvarez, Spain Mansheng Chu, China Louise Grondin, Canada Takeo Hoshino, Japan Yasuo Kishimoto, Japan Kejiang Li, China Chinho Park, Korea Martin Pei, Sweden
Buildings & smart cities Tom Leahy, Ireland (Chair) Christy Adelowo, Nigeria Yves Bamberger, France Rasmus Bramstoft, Denmark Seung Lee, Korea Vishaal Lutchman, South Africa	**Coupling** Rasmus Bramstoft, Denmark (Chair) Yves Bamberger, France Pradeep Chaturvedi, India Franco Davoli, Italy William D'haeseleer, Belgium Henrik Lund Frandsen, Denmark Tim Lieuwen, USA

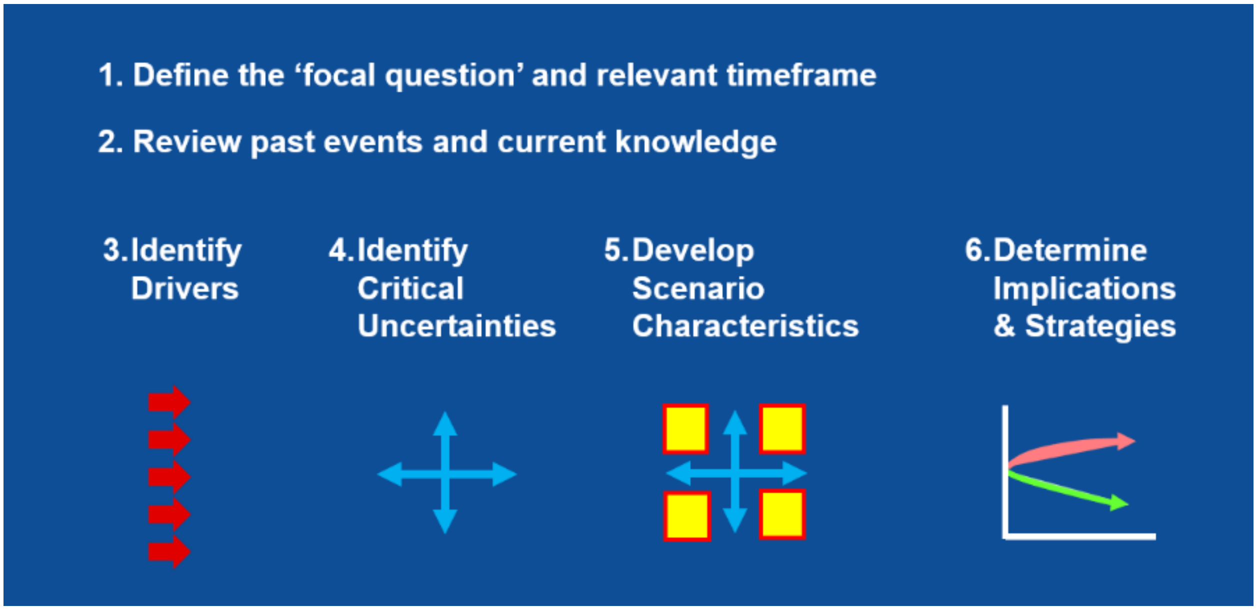
Report structure

In addition to the introduction, conclusions, CCS, hydrogen, and coupling chapters, this report contains a chapter on each industry sector. The structure of each chapter is similar (stating pertinent drivers, critical uncertainties, scenarios, and strategies), but not identical.

Identifying major long-term strategies for reducing greenhouse gas emissions associated with each industry sector constitutes the most important results of the Sequel Project. While there are strong commonalities among the strategies, regional and country differences are recognised and reflected in the conclusions.

Appendix 1: Scenario creation methodology

The six-step scenario creation methodology is summarised in the following figure.



For the Sequel Project, the focal question and time frame (>2040) were stated above. The past events and current knowledge are largely contained in the 2022 CAETS report. The drivers are the forces and factors that will impact the industry sector now and in the future. They include, for example, products, markets, policies and regulations. Critical uncertainties are those two drivers that impact the industry sector strongly while also being highly uncertain. From two selected critical uncertainties follow four distinct future scenarios. Some of the scenarios are typically seen as favourable, while others are not. Strategies can then be developed that will result in appropriate outcomes under all scenarios. Such strategies are called robust scenarios and constitute the primary objectives and outcomes of the Sequel Project.

References

[1] International Council of Academies of Engineering and Technological Sciences (CAETS), *Towards low-GHG emissions from energy use in selected sectors* (University Park, MD: CAETS, 2022), accessed June 21, 2024, https://www.newcaets.org/wp-content/uploads/2023/02/CAETS-ENERGY-REPORT-2022-22-January-2023.pdf.

[2] Shell, *40 Years of Shell Scenarios*, accessed June 21, 2024, https://www.shell.com/news-and-insights/scenarios/what-are-shell-scenarios/_jcr_content/root/main/section_509167378/promo/links/item0.stream/1652289755448/a0e75f042fee5322b72780ee36e5ba17c35a4fc6/shell-scenarios-40yearsbook080213.pdf.

[3] Shell, "The Energy Security Scenarios: Summary," Shell.com, accessed June 21, 2024, https://www.shell.com/news-and-insights/scenarios/the-energy-security-scenarios/_jcr_content/root/main/section_926760145/promo_copy_142460259_1698265813/links/item0.stream/1679345012896/4dccc89eba3c80899dc0e61b43ce07839d7899ee/energy-security-scenarios-summary.pdf.

[4] Alberto Behar and Sandile Hlatshwayo, "How to Implement Strategic Foresight (and Why)," International Monetary Fund, December 22, 2021, https://www.imf.org/en/Publications/analytical-notes/Issues/2021/12/22/Strategic-Foresight-at-the-International-Monetary-Fund-463660.

1. Forestry industry

Tom Browne, chair	Canada
Peter Axegård	Sweden
Ian de la Roche	Canada
Ludo Diels	Belgium
Richard Kerekes	Canada
Esa Vakkilainen	Finland

This chapter seeks to identify paths that the forest sector ought to take in the run-up to 2040 and beyond, based on the societal needs that will likely arise from the impacts of climate change and declining biodiversity after 2040. Forestry has great potential to tackle climate issues and replace fossil-based materials with bio-based ones, but the transition remains challenging.

While forest products are traded globally, raw forest resources are generally best transformed close to the resource. As a result, conclusions will vary to a certain extent from region to region.

Background

Forest sector overview and constraints

The global forest sector has a huge opportunity to store carbon while displacing a number of fossil-based products. Maintaining biodiversity, minimising negative impacts of land-use change, and respecting Indigenous rights and land ownership will be critical.

The costs of hauling biomass from the forest to processing facilities limit economies of scale, so priority must be placed on higher-value products, with low-value mixed residuals such as harvesting residues, thinnings, bark, sawdust and spent cooking liquors directed toward internal and local external energy needs.

Directing residuals to energy generation means the industry can be run essentially without fossil fuels. Technologies to increase energy efficiencies and exports are readily available for either retrofits or new mills. Two challenges constrain investment: the availability of enough wood within a sufficiently short trucking distance, and the absence of policy or regulatory frameworks that adequately recognise processes and products, other than fuels, with reduced carbon intensities.

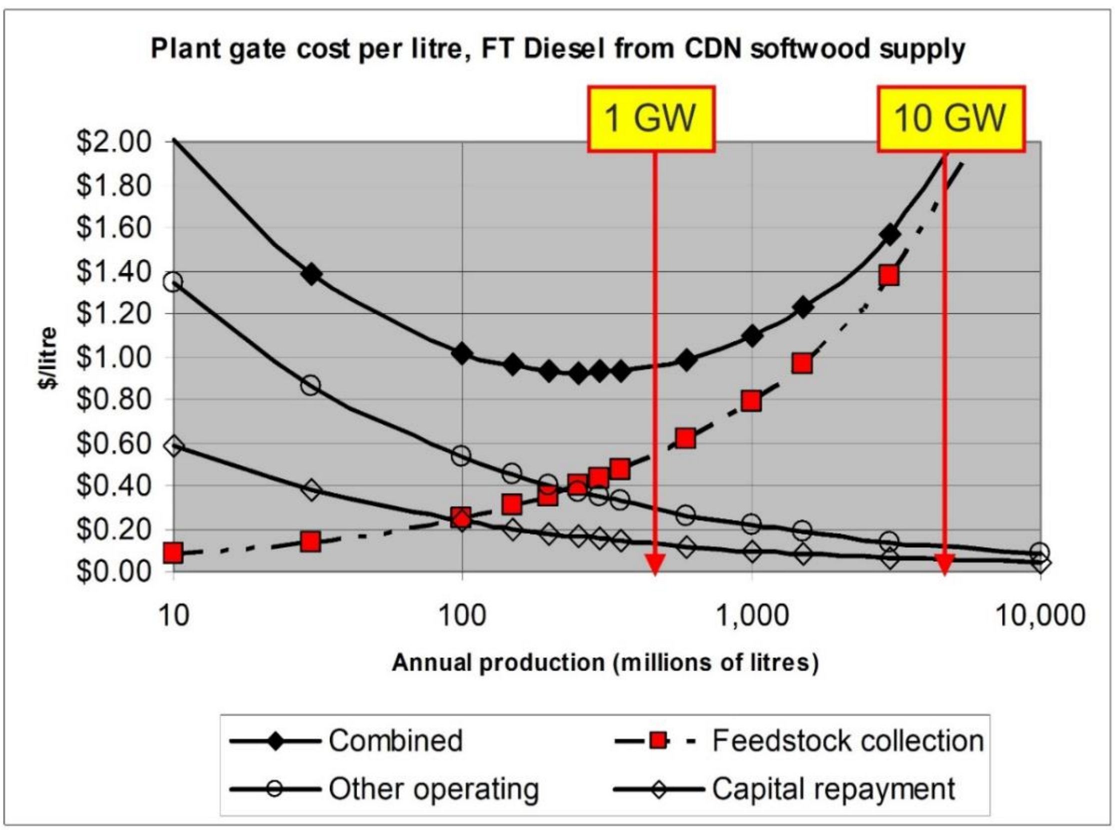
Feedstock transportation costs are often understated. The relative scales of current best-in-class pulp and paper assets, compared to typical petroleum refineries, are shown in table 1.1 in terms of material feed rate in GW.

Table 1.1: The world`s largest pulp mills versus petroleum refineries

Mill	Location	Feed rate	Units	GW input	Notes
Pulp mills					
AlPac	Canada	5,625	odt/d	1.2	Canada's largest pulp mill, 810 kt/y pulp capacity
Kemi	Finland	10,417	odt/d	2.2	Finland's largest pulp mill, 1.5 Mt/y pulp capacity
Três Lagoas	Brazil	22,569	odt/d	4.7	Two production lines totalling 3.25 Mt/y pulp capacity
Petroleum refineries					
Saint John, NB	Canada	300,000	bbl/d	21.2	Largest in Canada
Port Arthur	USA	630,000	bbl/d	44.5	Largest in North America
Port of Rotterdam	Netherlands	1,180,000	bbl/d	83.3	5 refineries, 58 mt/y capacity at 7.3 barrels/tonne
Jamnagar	India	1,240,000	bbl/d	87.5	Largest in the world

Note: Energy input per unit time contained in the feedstock, in GJ/s (GW), based on 18 GJ per oven-dried metric tonne (odmt) of wood, 6.1 GJ/bbl. Pulp mill yields are assumed to be 400 air-dried kg of pulp per odmt of wood supplied.

Figure 1.1: Plant gate cost per litre, Fischer-Tropsch diesel from Canadian softwood supply



As collection radius increases, marginal tonnes of wood need to be transported over longer distances, becoming more expensive. Economies of scale available to petroleum refineries are not achievable with wood, given current product values and carbon pricing. As shown in Figure 1.1,[1] marginal feedstock costs eventually overwhelm economies of scale.

With appropriate investments in R&D, scale-up and implementation, new technologies can help the forest sector become carbon-negative. Country-specific policies and incentives[2] and a move to higher value-added products[3] will be necessary.

Supply and demand scenarios to 2030

The forest industry uses both softwood (coniferous species) and hardwood (deciduous species), with end-use requirements driving the choice of supply.

No solid forecasts exist for supply and demand post-2040, but trends to 2030 are instructive. Global demand for sawn timber is expected to grow through 2030, combined with a reduced supply of sawlogs. Demand for softwood over the next decade will outpace supply by about 35 million cubic meters per year.[4, 5, 6]

European softwood sawlog supply is forecast to decline, driven by the spruce bark beetle outbreak in Germany, Sweden and Czechia and the virtual halt of all supply from Russia, Belarus, and Ukraine. This is combined with growing demand for sawn timber, driven by climate change initiatives to control CO_2 emissions and sequester carbon in the built environment. Future access to Russian wood will be key to EU supply and demand balances.

North America's softwood sawlog supply will meet demand, with supply shifting from Western Canada to the southern United States, which is the only global region (excluding Russia) with the ability to increase its harvest.

Fibre deficits in China will be alleviated by reduced infrastructure spending and investments in fast-growing hardwood plantations in southern provinces. Chinese economic growth will shift away from a high dependence on export and real estate development toward internal demand. Russia possesses abundant forest resources. Driven by China's domestic forest resource constraints and the demands of its sustained economic growth, it is anticipated that enduring cooperation in timber trade will continue between China and Russia. The Russian log export ban to Europe may eventually be reconsidered.

Better use of underutilised species such as aspen, rubberwood and palm, and non-wood species like bamboo, is now feasible. Bamboo typically exhibits faster growth rates and biomass accumulation compared to trees. It can be continually re-harvested in a fast-growing coppice plantation, and is also much more efficient at sequestering carbon dioxide than forests. In China, engineered bamboo scrimber (deconstructed bamboo stems) is currently used in flooring, furniture and shelter construction. Rubberwood and palm timber are also widely used in construction.

Brazil is the largest producer of bamboo after China. Growth rates of 3–5 m^3 stem wood/ha-y in Sweden compare with 40-45 m^3/ha-y in Brazil. The best Brazilian plantation yields about 80 m^3/ha-y; clones in tree nurseries yield 120 m^3/ha-y. Transportation costs are thus significantly lower than in northern climates, where wood fibre needs to be sourced over many more hectares for a given feed rate.

Crop improvement technologies can improve trees' resilience, leading to productivity improvements. But treating timber like an agricultural crop has pros and cons. Yield can be significantly increased, but biodiversity is near-zero in a plantation forest, and trees may be more vulnerable to attack from insects, fungi, etc. due to low genetic variability.

Demand

World forest cover in 2020 was just over 4 billion hectares[7], three-quarters of it located in South America, Russia, North and Central America and Asia. Net forest losses from 2010 to 2020 are estimated at 4.7 Mha/y, but some regions have seen net gains despite ongoing harvesting. This resource represents a huge carbon sink; if sustainably managed to preserve stored carbon, it also offers the opportunity to produce low, zero or negative carbon products to meet society's needs in a warming world.

Demand is expected to decline for most printing and writing paper grades, but will likely grow for four types of forest products:

- shelter systems (housing, infrastructure, etc.)
- packaging products
- hygiene products
- novel bioproducts to enhance or displace current petrochemicals

Drivers

The most significant geopolitical drivers affecting the forest sector will likely be the following, with impacts varying by region:

- population growth and age demographics
- demand for increased standards of living in the developing world, including changes in diets
- urbanisation and associated land-use change
- climate-driven impacts on people, infrastructure and ecosystems such as forests
- major shifts in the availability of naphtha and natural gas liquids for petrochemicals as fossil fuels are phased out
- mitigation of anthropogenic carbon emissions
- public views on forest conservation versus timber harvesting
- industry and government aversion to risk-taking and investment
- growing demand for sustainable consumer products
- shift to consumer pull rather than commodity push

The forest industry is becoming increasingly global. Past models of pushing commodity grades to low-value markets are being replaced by consumer-driven pull for value-added products. These trends are accelerated by fibre constraints (cost and availability). Pulp and paper mills are moving to bioproducts based on cellulose and lignin; within the solid wood industry, shifts include a move from commodity stud mills to specialty mills producing higher-value engineered products and systems.

Critical uncertainties

Disruptive technologies often lead to unexpected results. A list of highly disruptive or undesirable future scenarios follows, with strategies (technologies, policies, social changes, etc.) that should be developed now to respond to these scenarios. Strategies will hopefully be robust across multiple possible future scenarios, even those not modelled.

The following two axes (critical uncertainties) are proposed, defining four potential futures.

X-axis: Resource availability (high/low)

Wood, water and energy are key resources for the forest industry. Low availability of any of these resources impacts the sector's ability to operate or effect change.

Forests can be seen as either a carbon sink that should be left untouched or a source of green products arising from sustainable harvesting and active forest management. What are the impacts of drought, fires or insect infestations, above and beyond the loss of biomass? Availability of wood can be affected by both climate impacts and policies driven by clear voter preferences. Water depends on drought or flood conditions, which in turn impacts hydroelectric capacity.

At one extreme, climate change has reduced forest cover in 2040 through fires, insect infestations and drought. Shortages of water for drinking or hygiene are common. Hydroelectric generating capacity is reduced. Environmental movements, while well-meaning, have driven a "build nothing anywhere" approach that seeks to preserve forests as biodiverse havens for carbon storage.

At the other extreme, the scientific view of a working forest, consisting of healthy and growing trees, with older trees removed as they mature, has led to increased forest availability without impacting carbon storage or biodiversity. Reforestation and afforestation have reclaimed unused industrial, suburban and agricultural land, compounded by increased carbon storage in durable carbon-containing products. Forest management to reduce downstream flooding has improved hydroelectric stability, while climate concerns have driven major new investments in carbon-neutral energy sources. Solar power is common in urban areas, reducing the need for long transmission lines; peaking power demands are met by combustion of biomass residues or other renewables, such as wind backed by novel storage systems.

Y-axis: Public willingness and economic capacity to take action (high/low)

This could also be called the "social value" axis.

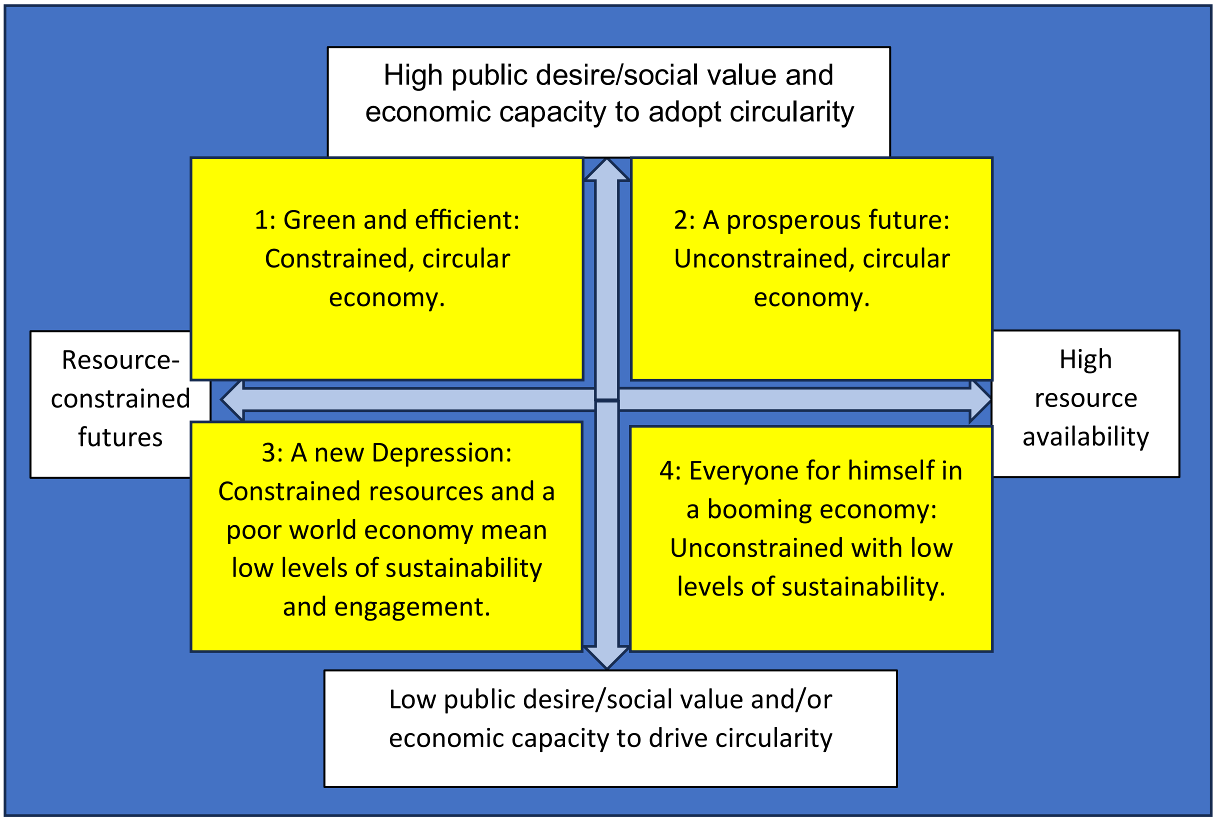
Public reaction to climate news falls within two extremes. At one extreme, there is a strong desire to take action, including making personal choices about one's own carbon footprint; there is a recognition that nature provides "ecosystem goods and services" that benefit humanity, but are not recognised or valued by traditional economic theory. The costs of these benefits need to be quantified and borne by more carbon-intensive options; voters and politicians are prepared to implement the necessary carbon-pricing policies, and industry is prepared to invest once consistent and permanent carbon policies are in place. Implementation of the circular economy and design for end-of-life begin to decouple economic growth from increased resource extraction.

At the other extreme, apathy and a reluctance to take action arise from a common feeling that the climate problem is too big and nothing we do will change anything. Especially in economically difficult times, citizens are more concerned about where their next meal is coming from and are financially unable and/or unwilling to make enlightened, but more expensive, carbon-neutral choices. Government action that appears to impose higher costs on citizens results in wide-scale resistance, and politicians see support of circularity as vote-losing.

Essentially, this axis is a measure of society's desire and/or economic ability to engage in the efforts needed to achieve a circular, net-zero, climate-friendly economy. A low scenario may arise because economics are so poor that investments are not possible, or because climate fatigue drives governments, industry and citizens to lose their appetite for change.

Scenarios

Figure 1.2: Scenarios



Scenario 1: Green and efficient

This scenario (see Figure 1.2, upper left) is characterised by constrained resources and strong action on circularity. By 2040, climate change has reduced forest cover; remaining forests are preserved as biodiverse havens for carbon storage. Drought has reduced availability of clean drinking water and hydroelectric generating capacity.

As a response to these shortages, government policies have encouraged large-scale investments in green and carbon-neutral technologies. These have generated well-paying jobs in a range of sectors, including forestry, where making better use of a reduced resource has led to a focus on durable, long-life, higher value-added products at the expense of short-life, disposable products. Examples include bioplastics in reusable and recyclable consumer goods such as automobiles and home appliances. Use of wood as a construction material will grow, even when steel or concrete are cheaper, due to its reduced carbon footprint and the benefits of prefabrication approaches to onsite assembly.

A range of local, distributed green-energy systems have been adopted along with large-scale renewable energy systems. Fewer automobiles, less gridlock and improved public transit allow the urban consumer to invest in climate-smart choices, such as heat pumps or better home insulation, that may have long payback periods; government subsidies help to accelerate this trend. Greater energy, water and material efficiencies may initially be driven by climate-induced shortages, but eventually become self-perpetuating, as using less leads to improved quality of life for all. Societal wealth (both personal and policy-driven wealth, such as healthcare, childcare and education) makes life better for everyone; economic growth is decoupled from increased resource consumption.

Scenario 2: A prosperous future

This scenario (upper right) is characterised by no resource constraints and strong action on circularity.

Increased forest availability has been achieved without impacting carbon sinks or biodiversity, partly through reforestation and afforestation. Better control of flood waters has improved hydroelectric stability, and nuclear power, along with decentralised solar and wind power supported by novel energy-storage systems, provides the energy needed for electrification of the transport system.

Investments needed to develop green and carbon-neutral technologies have generated well-paying jobs in a range of sectors, including forestry. As with Scenario 1, benefits in urban areas accrue due to changes in transportation infrastructure. Greater energy, water and material efficiencies lead to improved quality of life and societal wealth. This prosperous and green future makes the best use of forests, displacing more carbon-intensive solutions in a wide range of markets.

Scenario 3: A new depression

This scenario (lower left) is characterised by constrained resources and a low capacity or desire for action on circularity.

As with Scenario 1, climate change has reduced forest cover. Water shortages are common. A “build nothing anywhere” approach seeks to preserve forests as biodiverse havens for carbon storage. Unlike Scenario 1, however, the economy is doing poorly. Housing is unaffordable; food banks and homeless shelters are overwhelmed. The costs of climate change action are perceived as high. Responding to voters’ concerns, policy-makers have rolled back carbon taxes and regulations. Poverty leaves no room to improve household energy efficiency, even with decent payback periods, simply because the investment dollars are not available. High-cost urban housing forces workers to live in distant suburbs poorly served by public transit, driving automobile ownership rates up and delaying transport fleet electrification, as these workers are not well-positioned to replace aging gasoline-powered vehicles.

The bio- or forest-based attributes of a product become far less important than its purchase price; and if circularity requires costs or efforts to reuse, recover or recycle, then those products will wind up in waste streams, with potentially drastic long-term consequences. The impact on the forest sector is potentially dire, with layoffs and mill closures driven by reduced resource availability and declining consumer capacity or desire to spend on anything but essentials.

Scenario 4: Everyone for themselves

This scenario (lower right) is characterised by no resource constraints and low capacity and/or low desire for action on circularity.

As in Scenario 2, resource availability is not an issue. The world is awash in cheap resources, at least for a short time; the economy is booming. Citizens are happy to ignore the potential long-term pitfalls and take advantage of this situation by consuming. Possibly because of climate fatigue and a sense that it's too late or impossible to reverse climate impacts, the focus is on immediate personal gratification, rather than the health of the broader society: the "tragedy of the commons" writ large. Concerns about circularity fade, as there are no economic drivers to implement it. The forest sector can do well in this booming world, if only for a short time, even if the carbon neutrality of its products is not valued, but the product mix will be tailored to consumer demands, rather than net-zero imperatives.

Strategies

The forest sector will need to become carbon-neutral or even carbon-negative as the economy pivots away from fossil fuels.[8] If faced with each of the scenarios above, what strategies should the forest sector adopt today? Which strategies might be common to two or more scenarios and therefore more likely to be a useful response to a potential future, even one not explicitly described here?

The working group has identified four strategies of potential value to the forest sector, ranked in decreasing order of importance:

1. Quantifying, managing and increasing the value of forests, in particular:

- preventing the loss of existing forests through fires, drought and infestation
- expanding the carbon-storage capacity of our forests
- expanding the land area available for forests for carbon storage and harvest

2. Designing, producing and offering affordable, novel products for circularity, long-term carbon sequestration and end-of-life, using sustainable energy resources for each step of the process from stump to products to end-of-life

3. Minimising the generation and maximising the valorisation of residuals

4. Training highly qualified personnel

Quantifying, managing and increasing the value of forests

No forest-based products will be available if this resource is not protected and valorised, respecting both the economic value of forest products and the value of carbon sequestration, whether in forests or in durable, long-life forest-based products.

Quantifying forest value

The economic value of forests is easily measured in terms of sales volumes. The value arising from forest-based ecosystem goods and services is far less quantifiable.

These goods and services include biodiversity, carbon sequestering and storage, watershed management and associated flood and drought mitigation, air quality and cooling in urban environments, and recreational value, such as hunting and fishing, ecotourism, and cultural and spiritual aesthetics. In the absence of agreed-upon value propositions for these attributes, they are hard to compare to the economic value of construction materials, pulp and paper products, biochemicals, biomaterials or wood-based textiles. Value propositions for these goods and services will need to be clarified, quantified and expanded. This will require input from Indigenous communities, citizens and society, governments, industry, non-governmental organisations and other interested parties.

In this context, there is also insufficient data or evidence-based knowledge to pronounce definitively on the carbon neutrality of bioenergy or biofuels; this is therefore a critical research need.

Managing and increasing forest value

An adequate and robust supply of wood fibre is critical for the forest products industry.

Maintaining and increasing forest value will require addressing climate-change impacts. The impact on boreal forests, where temperatures are increasing two to four times faster than elsewhere, or in southern forests facing increased drought or flooding, will be significant. This includes not just the type of tree that will grow in a specific region, but also the nature of forests as an active carbon sink. Effective forest management approaches, including managing the impacts of forest fires, will be needed to ensure resilience and grow carbon storage. Controlling and reducing the incidence of forest fires in particular will be critical going forward; carbon emissions from the 2023 Canadian forest fire season were on par with large nations' yearly fossil-fuel sector emissions, exceeded only by the amount of carbon released annually by India, China and the USA .[9]

Deforestation must be reversed through reforestation and afforestation; forest growth in some jurisdictions is now higher than removals,[10] but more work is needed. Resilience may require rethinking which species are planted where and adopting active crop-improvement technologies from agriculture.

Achieving balance between extracting carbon-neutral products and preserving the forest's natural contribution to ecosystems will be critical, especially in resource-constrained scenarios. This will require prioritising carbon sequestration in long-life products such as buildings or durable consumer goods, rather than creating short-life, disposable products.

Novel harvesting responses to these sometimes conflicting objectives will be driven by new precision forestry tools, using drone and satellite data and analysis by IT and AI systems.

There is an ongoing shift away from sustained yield management, with its emphasis on maintaining a continuous supply of timber, toward a more social and sustainable approach. The objective is to maintain and enhance the forest's socioeconomic and ecological value for present and future generations.

Designing novel products for circularity and end-of-life

Circularity

A circular economy requires design for end-of-life reuse and recovery, decoupling economic growth from increasing resource extraction by effectively reusing existing resources. Adopting circular thinking and action in all stages of forest product development, design and production will be key to meeting climate targets.

Where possible, durable products with an extended lifespan from stump to disposal should be prioritised over single-use products with a short lifespan. Better material use that maximises product and value generated per cubic metre of wood consumed will be critical.

Particularly in the case of buildings, end-of-life planning needs early attention by designers, engineers, architects, building contractors and specialists. End-of-life begins with reuse and recovery; ease of disassembly in construction and demolition activities will be critical.

Where products can't be reused or recovered, recycling will remain important. Contamination of these streams degrades their value. Sorting processes, beginning at the point of collection (whether residential recycling or construction and demolition processes), will become more critical. Manual sorting processes will increasingly be automated.

Recycling processes can require heat, power and water, and generate residues and carbon emissions. In a future where no fossil fuels are burned, biodegrading, composting or combustion for energy generation remain the last choices, as these release carbon dioxide.

Novel products

A low-carbon solution to worldwide housing crises will be essential. Demand for wood, today mostly softwood, in construction of mid-rise and residential buildings will increase, while burning wood for heat, power and cooking will be under pressure in the context of storing carbon even if concerns around particulate emissions can be addressed. Alternative sources of fibre, such as hardwood or residues, may need to be considered in the production of engineered wood products.

The need for shelter in less-developed countries will drive prefabrication and modular construction of structural wood components, in the context of local conditions such as type of wood available, climate, earthquakes, necessary insect resistance, etc. Cross-laminated timber and other engineered wood products will be complemented by new technologies, such as 3D printing using a mix of wood fibre and adhesives. These products offer significantly increased strength over conventional dimensional lumber, leading to simplified design and increased material efficiency for a given strength requirement.

The paper-based packaging sector includes bags, wraps, inserts and boxes. Performance characteristics of food-grade products requiring novel bio-based coatings are critical to public hygiene and safety as well as minimising spoilage.

The packaging sector is growing, driven by ease of recycling, public desire to replace plastic containers, and increasing home delivery. Nevertheless, recycling consumes water and energy. Public acceptance for this use of resources may force the need for reusable, rather than recyclable, containers. Development of lightweight, reusable paperboard containers for shipping goods, and the logistics to make multiple use of them, will be an important step.

The hygiene, health care and hospital-grade sectors are expected to grow, due to an aging population and growing affluence in the developing world. Hygiene products include facial and toilet tissues, towels, incontinence pads, diapers, hospital gowns, various hospital-specific grades, and low-volume, high-value wood-based antibacterial products. These are essential single-use products designed to protect health and prevent spread of disease. Novel performance characteristics, such as high water absorbance, will be critical. Disposability is an issue, but developments such as flushable diapers and wipes may allow for disposal in existing sanitary systems if these are properly designed and operated.

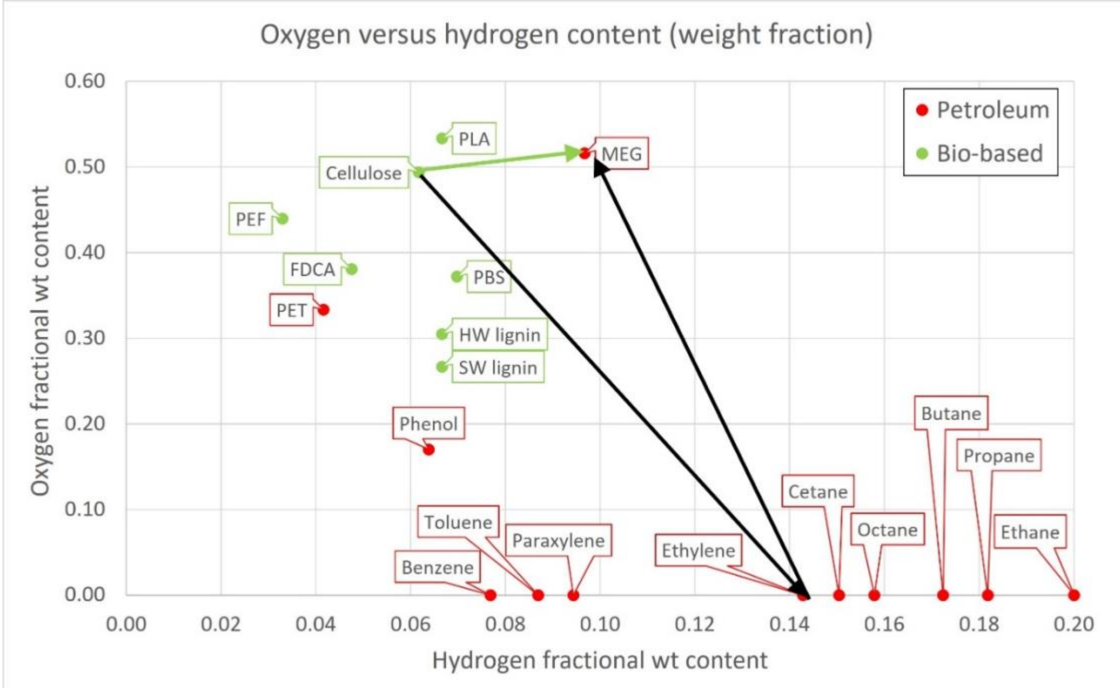
Wood-based replacements for cotton and synthetic fibres are already available. Cotton requires high water, pesticide and fertiliser use, while synthetic fibres are made from fossil fuels and offer poor end-of-life options. New processes to convert wood-sourced cellulose to a textile fibre avoid the polluting chemistry of traditional viscose-to-rayon processes. The potential for large-scale replacement of cotton is large and potentially disruptive. In addition to the existing Lyocell process, the new SPINNOVA[11] and Kuura processes are examples.[12,13] Other novel products may be based on fibrillated cellulose.[14] Cellulose nanofibrils can form stable water emulsions at low concentration and may replace both polyacrylates and emulsifiers in personal care products.[15]

Lignin, hemicellulose, cellulose and extractives can be converted to substitute, partially or fully, for a range of products, such as resins and polymers, currently made from petroleum. Pathways today include cellulose-to-sugar platforms[16,17] and lignin-to-phenolic applications.[18] Making good use of all components in the feedstock is critical to optimising use of biogenic carbon, minimising residual streams and ensuring reasonable process economics. Strong basic and applied research programs are needed to implement these pathways, along with support for scale-up of promising approaches from laboratory scales through to full commercial scale.

Products may be molecularly identical replacements for existing petrochemicals; new functionally identical molecules; or new-to-the-world molecules with unique characteristics. Biodegradability or compostability may be of primary importance for single-use products with a short expected lifespan. Interest is growing in the EU, but legislation focuses solely on recycled content and not bio-based content; both represent responsible use of raw materials in a circular economy.

Biomass molecules differ from most fossil-based hydrocarbons in the presence of oxygen and relative lack of hydrogen. Converting cellulose to ethylene requires deoxygenation and hydrogenation to make best use of the carbon content in biomass. An alternative is to target oxygenated hydrocarbons.[19] Current approaches bypassing the benzene molecule in the path from lignin to phenols, or bypassing the ethylene molecule in the path from cellulose to monoethylene glycol (MEG), are consistent with this approach, as shown in Figure 1.3.

Figure 1.3: Oxygen vs. hydrogen content in petroleum and bio-based products



https://www.wiley.com/en-us/Introduction+to+Chemicals+from+Biomass%2C+2nd+Edition-p-9781118714485

Wood-based fibres can replace man-made fibres in composites such as automotive components. Initially limited to non-structural components, improved fibres and resins will find use in load-bearing applications. End-of-life will be critical; composite materials are difficult to recycle, regardless of bio-based nature. Adhesives that can be de-bonded and other end-of-life approaches need to be identified at the design stage.

Production facilities

Modern facilities will be needed to make the products described above.

Conversion of solid wood from dimensional lumber to novel engineered-wood products, such as cross-laminated timber, oriented strand products or laminated veneer lumber, will require new plants and investments, but the technologies are well-known, and the costs and complexity are significantly less than for pulping or biorefinery processes.

Conversion to products other than solid wood will take place in facilities that may not make conventional pulp and paper products. The modified kraft pulp mill efficiently separates cellulose and lignin. Novel pathways such as acid or enzymatic hydrolysis, Organosolv pulping, deep eutectic solvents and other ionic liquids, and gasification and synthesis may be used. The technology readiness levels of these pathways are generally low to medium, and the economics poor, but breakthroughs are possible.

The fibre, water and energy efficiencies of a modern pulp mill are higher than in an older one. A program of replacing multiple older small mills with a single state-of-the-art super mill, limited in scale only by wood supply, may offer greater benefits compared to improving existing assets. Super mills will produce a range of products beyond traditional pulp, heat and power. Water shortages may accelerate this trend.

Metsä has built a new 1.3 Mt/y kraft pulp mill at Äänekoski,[20] Finland, at a cost of €1.2 billion in 2017. Metsä invested a further €2 billion in a 1.5 Mt/y mill at Kemi.[21] Both facilities generate about 2.5 times the energy required by the mill, providing significant revenues in the form of sales of power to the grid and heat to local district heating utilities.

In South America, CMPC is building a 2.5 Mt/y pulp mill in Rio Grande do Sul. Investment, including road and port infrastructure, is about US$4.6 billion. Celulosa Arauco y Constitución is planning a new pulp mill of similar scale in Mato Grosso do Sul, at an estimated cost of US$3 billion (2022 $).

A wood-based biorefinery, mimicking the petroleum refinery, can be co-located within the chemical industry rather than close to forests. UPM's bioproducts plant[22] is located at the petrochemical park in Leuna, Germany. The ports of Antwerp, Rotterdam and Amsterdam, along with the Rhine–Ruhr area, offer another potential location, if wood (perhaps in the form of pellets) can be supplied at reasonable cost. Other integration opportunities will arise as market demand leads to investments.

In any case, investments on the order of US$5 to US$10 billion per site will be necessary.

Energy implications

Energy cost reduction has long been a priority in the pulp and paper industry.[23] Drying is one of the largest uses of energy when making paper and market pulp, and requires intensified R&D in what has often been neglected as old technology.[24, 25]

Significant amounts of energy are used to heat fresh process water. Reducing water use is thus a critical step to reduce energy use.[26] As water use is reduced, energy use declines, but there is a non-zero water use level corresponding to minimum energy use.[27] Extremely high water recycle rates require improved removal of accumulating contaminants; development of "kidneys" to achieve this goal' remains an active research area.

Modern kraft pulp mills also export energy. Systems burning pulping residues, bark and other residues deliver excess heat and power to local district heating and electrical grids. New recovery boilers are proven technology and are significantly more efficient than existing systems.[28] A program of retrofitting existing mills or designing and building super mills will ensure the best use is made of the available biomass-based fuel.

Carbon capture, applied to biomass-fueled combustion processes, carries the added benefit of removing biogenic carbon from the flue gas. Process-related carbon dioxide generated by the lime reaction can also be captured along with the energy-related carbon dioxide. The situation is improved if the kiln is operated with excess oxygen, perhaps left over from hydrogen production via electrolysis, instead of air.

Minimising the generation and maximising the valorisation of residuals

Forest thinnings and harvesting, debarking and sawmill residues are currently directed to energy. There is a lack of hard data on the need to leave organic matter in the forests versus removing it for reuse. In the southern United States, roundwood is going to pellet users for power generation in the U.K. and elsewhere; this is not the best approach to climate issues. However, in the absence of locally-sourced biomass, the ARA ports of

Antwerp, Rotterdam and Amsterdam and the Rhine–Ruhr area have a ring of high-tech industries[29, 30] that could make non-thermal use of these pellets for bioproducts.

Boiler ash, effluent treatment sludges (biosolids) and paper recycling sludges are challenging. Some are used in soil amendment or cement and concrete, but the buildup of contaminants in soils will be a problem, depending on the residual material. Land-spreading of dried biosolids from effluent treatment is in place in some locations, such as Kemi, but prohibited elsewhere; this approach depends at least partly on local regulatory conditions and public perception.

Training of highly qualified personnel

Attracting qualified teachers, mentors, trainers and students to the industry is critical and depends on a positive societal view of forestry. Collaborative education systems spanning universities and institutes will be critical in growing enrollment to levels required by the increasingly global nature of the industry. Low-cost distance learning will enable remote regions and developing countries to participate in advanced education.

The forest industry has shown itself capable of being a positive factor in mitigating climate change, rather than an aging sunset industry. Factual information about the industry must be supplied to the public, potential future employees and policy-makers. It will be critical to promote the forest industry as a challenging and interesting place to work while ensuring that job openings exist, at every level from mill operations to the innovation space.

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2. Agriculture and food

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The agriculture and food sectors, producing food and fibre, are an integral part of global ecosystems that include complex phenomena such as biodiversity and carbon sequestration. The latter are of critical importance to the global carbon cycle (GCC). Humans have become the most influential species in these global ecosystems. This chapter addresses technological and non-technological approaches to rebalancing the GCC in the agriculture and food sectors to avoid catastrophic global warming and other deleterious effects.

Agricultural and food ecosystems are special in relation to greenhouse gas (GHG) emissions in that they are part of the problem, but also part of the solution. Food production systems are significant emitters of greenhouse gases, largely through animal (ruminant) methane, nitrogenous fertilisers, waste, and energy usage. However, they are also part of the solution to emissions reductions, by virtue of their capacity to sequester and store carbon in healthy soils. The potential to substantially increase carbon sequestration exists because the health and carbon content of soil in many regions can be increased.

In this chapter we identify strategies, including technologies, that can optimise the functioning of agricultural and food ecosystems consistent with ecological principles that safeguard the natural capital of our planet and align with the 1.5°C trajectory of the Paris Agreement. That trajectory, first published in the Intergovernmental Panel on Climate Change's Special Report in 2018, was subsequently incorporated into many other documents and national policies.

The present chapter is written at a high level and is based on the premise that agriculture and food are one coherent sector where strategies for agriculture (i.e., the food-producing sector) are equally applicable to food (i.e., the sector where primary agricultural commodities are processed into food products). Agriculture also makes major contributions to other sectors: for example, materials, clothing and energy. Similarly, the food sector contributes to the production of animal feed and numerous chemical products. A detailed exploration of these contributions falls outside the scope of this chapter, which is primarily focused on greenhouse gas emissions directly related to primary agricultural and food production activities.

It is important to recognise that agriculture and food constitute a sector of local, regional, national and international significance and connectivity. Changes in one geographical region can have profound implications for regions far away.

Detailed explanations are provided in the Appendix to help clarify some of the concepts outlined in the following pages.

Drivers

Non-technical:
• Lack of understanding of our planet's lifecycles, in particular the importance of the global carbon cycle and its relationship to human activities in terrestrial ecosystems (crops, grazing lands, forests, etc.) • Subsidies that promote unsustainable practices and engineering analysis of these subsidies to avoid negative consequences • Trade barriers based on protectionist practices, with a particular focus on barriers based on climate change mitigation that transfer responsibility from one region to another • Growth of global middle classes and their need for higher quality foods, including animal-based products, largely protein • Agriculture and food wastage across the value chain up to the consumer • Global population growth and prosperity • Transformation of farmland to urban development or infrastructure • Adequately and globally implemented carbon pricing (costs on negative externalities and income to support positive externalities)
Inputs and feedstocks:
• Adequate pricing of positive and negative externalities to support inputs and feedstocks that align with GHG mitigation and atmospheric carbon removal and with the Paris Agreement 1.5°C trajectory
Products:
• Adequate pricing of positive and negative externalities to support agricultural products and services that align with GHG mitigation, the Paris Agreement 1.5°C trajectory and atmospheric carbon removal • Information technology and artificial intelligence applied to product logistics, consumption or reducing food waste
Technologies:
• Increased per-hectare yields through the application of innovative technologies, especially in lower-yielding regions, for growing and more prosperous populations • Farming technologies that consider ecosystem restoration for low GHG emissions and long-term carbon sinks with strong carbon removal. Ecosystem health should be objectively measured and aligned with carbon sequestration • Energy and nutrient recovery from waste streams to avoid emissions from crop and food production and fertiliser manufacturing, use and application • Indoor or urban farming as an alternative to conventional farming. Its applicability must consider all externalities: for example, use of carbon-neutral

energy, water and fertiliser consumption and adequate sewage treatment systems • Renewable energy technologies that mitigate emissions; for example, by anaerobic digestion of agriculture and food waste and by solar systems that provide excess electricity for export to the grid • Land-use and unsustainable development practices creating unsustainable transport systems motivated by geographic competition
Transportation and processing systems:
• Processing, logistics, packaging and final use that avoid emissions and adequately price in positive and negative externalities, including GHG mitigation aligned with the 1.5°C trajectory of the Paris Agreement • Transportation is critical for food and other agricultural goods. Emissions from this sector are a moderate percentage of the total and could be mitigated through improved logistics, transportation options, etc.

Critical uncertainties

Critical uncertainties are those drivers that are highly uncertain and important to the long-term future of the agriculture and food sector. Two critical uncertainties were selected, leading to four distinct scenarios:

Y-axis: Natural capital and ecosystem services, ranging from understood and valued to not understood and valued

X-axis: Advanced technologies, ranging from available to unavailable

Scenarios

Figure 2.1: Scenarios

Natural capital and ecosystem services that support life are understood and valued

1. Struggling food and agriculture sector

- Agriculture and terrestrial ecosystems continue to be large sources of emissions; little alignment with Paris Agreement Trajectory
- Low soil organic carbon sequestration
- Healthy soils and ecosystems at risk
- Business-as-usual technologies
- Business as usual in development of modern food/feed processing systems
- Business-as-usual subsidies and poor understanding by natural policy-makers globally
- Protectionism and low international competitiveness

2. Thriving food and agriculture sector

- Agriculture and terrestrial ecosystems supported by policy to mitigate emissions and sequester carbon as soil organic carbon and biomass
- Alignment with Paris Agreement trajectory
- Non-technical objectives met
- Healthy soils and ecosystems: nature-based solutions fully deployed
- Existing technologies improved and new technologies developed and used
- Strong workforce and innovation capabilities
- Advanced technologies to design and implement energy and nutrient recycling, organic matter recovery, waste and residue avoidance, etc.

Advanced technologies and engineering solutions

Unavailable ← → ***Available***

3. Declining food and agriculture sector

- Public and private decision-makers do not value natural capital and ecosystem services that support life; regulations are not science-based
- Soils and ecosystems degrading; no nature-based solutions
- Availability and affordability of inputs and feedstocks is ideologically based
- Trade barriers and subsidies rule
- Advanced technologies only marginally available and used
- Value chains used for trade wars
- Rural out-migration and instabilities
- Education and innovation systems imperiled
- No alignment with Paris Agreement 1.5°C trajectory

4. Imperiled food and agriculture sector

- Decision-makers and urban societies promote and support ideologies instead of science
- Agriculture and terrestrial ecosystems increase GHG emissions
- No soil organic sequestration or increased carbon sinks
- Soils and ecosystems imperiled
- Declining rural communities
- Ideology impedes development and implementation of science- and engineering-based solutions
- Protectionism, subsidies that promote trade wars, no international cooperation
- Each country on their own, climate change rampant, no commitment to Paris Agreement targets

Natural capital and ecosystem services that support life are not understood or valued

Strategies

1. Educate urban populations and decision-makers about the importance of terrestrial ecosystems to human subsistence and about the fact that agriculture is an important tool for their improvement. Promote understanding of atmospheric carbon removal by increasing organic carbon of soils and biomass in the agriculture sector and of other key GHG mitigation technologies increasing energy efficiency and nutrients reuse. Specific strategies are:

    a. Development of capacity-building programs to enhance teachers' knowledge of the importance of agriculture and GHG mitigation technologies as key to the global carbon cycle and to climate change mitigation.

    b. Development of global communications programs to enlighten all citizens on the role of farming and farmers as long-term stewards of nature on the front lines of removing atmospheric carbon emitted by other human activities, such as fossil-fuel combustion.

2. Support farmers and inland communities by providing engineering services and tools to implement technologies that mitigate GHG emissions and recycle energy, nutrients, water, organic matter, etc. Create long-term carbon sequestration projects and sinks through carbon removal, where possible. (See section 2 of the Appendix, "The natural carbon cycle and agriculture.")

3. Transform organic matter dump sites and waste streams into energy production systems through innovative technologies and adequate costing. Replace chemical nitrogen fertilisers with organic nitrogen compounds wherever possible. (See section 2 of the Appendix, "The natural carbon cycle and agriculture.")

4. Agriculture is currently undergoing a technological revolution led by data management, or AgTech. Many of these technologies rely on information gathered by satellites, drones, farm machinery, etc. This information must be made more widely accessible and members of the agriculture and food sector must be given the expertise to use the data for appropriate decision-making. AI tools are needed to support decision-making, but must be tempered by human expertise based on experience, logic and regional knowledge.

5. International and multilateral organisations, with the support of the private sector and engineering academies, should negotiate accords that avoid protectionism and trade barriers that limit capacity to implement new technologies and improve practices in developing countries, as well as imperil their ability to mitigate emissions or remove high volumes of carbon from the atmosphere.

6. The complexity of ecosystems in the agriculture sector is such that the brightest, most committed persons should be attracted to transforming agriculture from an emissions source to a long-term carbon sink, while continuing to produce more and better quality agricultural and food products for growing populations everywhere on Earth.

Appendix

Index

1. Agriculture and nature: an ecosystem perspective of agriculture

Many authors claim that now is the era of the Anthropocene; in other words, Earth and its systems and cycles are dominated by human activity. However, human well-being is still dependent on the ecosystem services that make life possible. Despite ample evidence of this fact, these services are taken for granted by many decision-makers and societies.

The ecosystem services that allow humans to have food, clean water, fibres and many other materials and the indirect benefits of biodiversity and natural amenities (which include pollinating species, among many others) are completely disregarded in economic and social systems that do not place a cost on negative externalities or attribute a source of income to positive ones. This lack of consideration of these vital natural activities is addressed as part of the climate change agenda via the carbon-pricing mechanisms many countries are implementing and in Article 6 of the Paris Agreement.

2. The natural carbon cycle and agriculture (methane cycle and nitrous oxide cycle)

Many publications and authors dub the greenhouse gases (CO_2, CH_4 and N_2O) polluting gases, rather than an integral part of global ecosystems. This unfortunate label has led to billions of people believing that these gases are alien, toxic chemicals in our atmosphere and that their emissions should simply be banned. Most humans do not have a reasonable understanding of how life on Earth is created and supported or how important agricultural activities are. From small flocks of sheep and goats in isolated places to extensive plantings of the three main cereal grains and all the other plants we have domesticated, these activities are the foundation of the cycles that support life today, particularly human life.

For example, a program to eliminate cattle herds has recently been promoted by government officials in Argentina, a country of grasslands. These programs simply focus on CH_4 as reported by the national inventory, completely disregarding the dynamics of ecosystem services and the millions of hectares of natural grasslands that co-evolved with ruminant animals capable of using the cellulose they produce. The resultant ecosystems have provided and will continue to provide an equilibrium between ruminants and the tremendous vegetal, insect and animal biodiversity that depends on these ecosystems. These political decisions to eliminate agricultural activities are supported by non-scientific activism and are based on ideologies that completely disregard science and the necessary knowledge needed to manage and improve these ecosystems.

The work of the Global Carbon Project[1] has been critical in helping to understand the importance of the natural carbon, methane and nitrous oxide cycles and their modification by anthropogenic GHG emissions. This group of scientists has explained very clearly how the global carbon cycle is much larger than the CO_2 emissions generated by fossil-fuel combustion, etc.

As can be seen in the upper right corner of Figure 2.2, natural carbon cycle emissions and removals equal 800 GTonnes of CO_2 per year.[a] This massive carbon cycle, which initially incorporates the carbon in CO_2 into simple sugars through photosynthesis and then into many other organic molecules like cellulose, proteins, fats, etc., is an inherent part of agriculture and all cultivated ecosystems, incorporating 500 GTonnes of CO_2. This absorption and the subsequent emissions through respiratory processes are entirely natural and occur in all terrestrial ecosystems. Oceans absorb and emit the remaining 300 GTonnes of CO_2 through various biological and chemical processes.

Annual anthropogenic emissions of CO_2 equal 41 GTonnes; of these, 11 GTonnes are absorbed by terrestrial ecosystems (natural lands and those under agricultural and forest production); 10 GTonnes of CO_2 are absorbed by the oceans; the remaining 19 GTonnes remain in the atmosphere, causing global warming.

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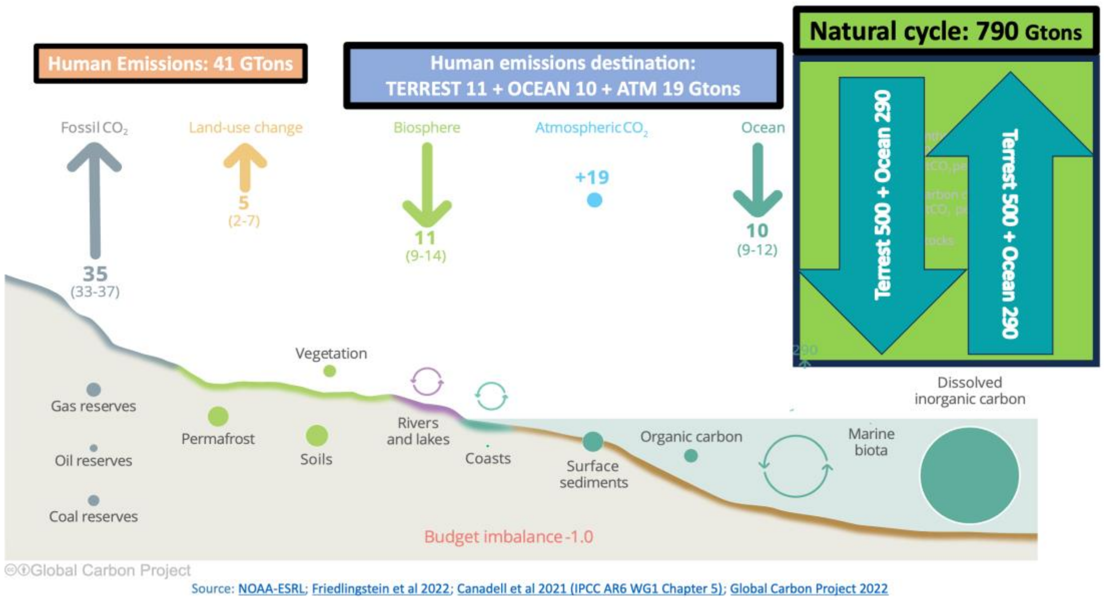
[a] 1 GTonne = 10^9 tonnes

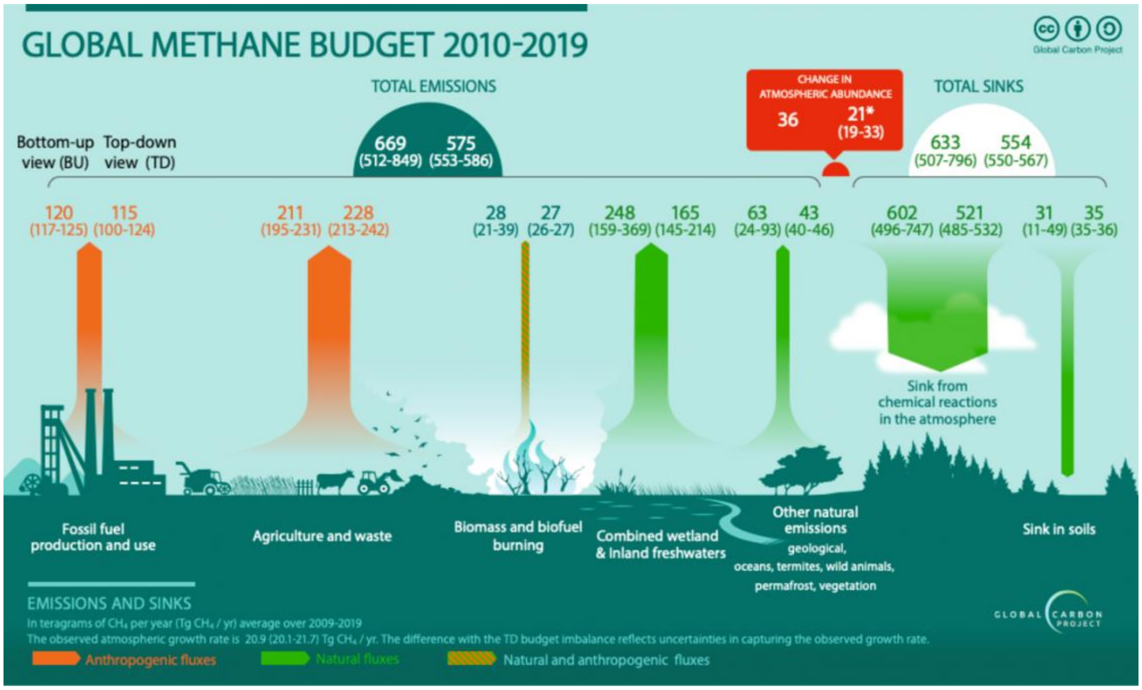
Figure 2.2: Anthropogenic perturbation of the global carbon cycle for the decade 2012–2021.[2] (Note: The boxed text was added to the figure and the numbers refer to GTonnes CO_2/year.)



After the Paris Agreement was signed in 2015, it was understood that agricultural soil is a phenomenal carbon sink, thanks to the life that exists in its upper layer, allowing plants and animals to thrive and prosper above. Therefore, as we present in the following section, the greatest engineering challenge humanity faces is improving this natural carbon cycle so that more carbon is sequestered in soils, biomass and other carbon sinks.

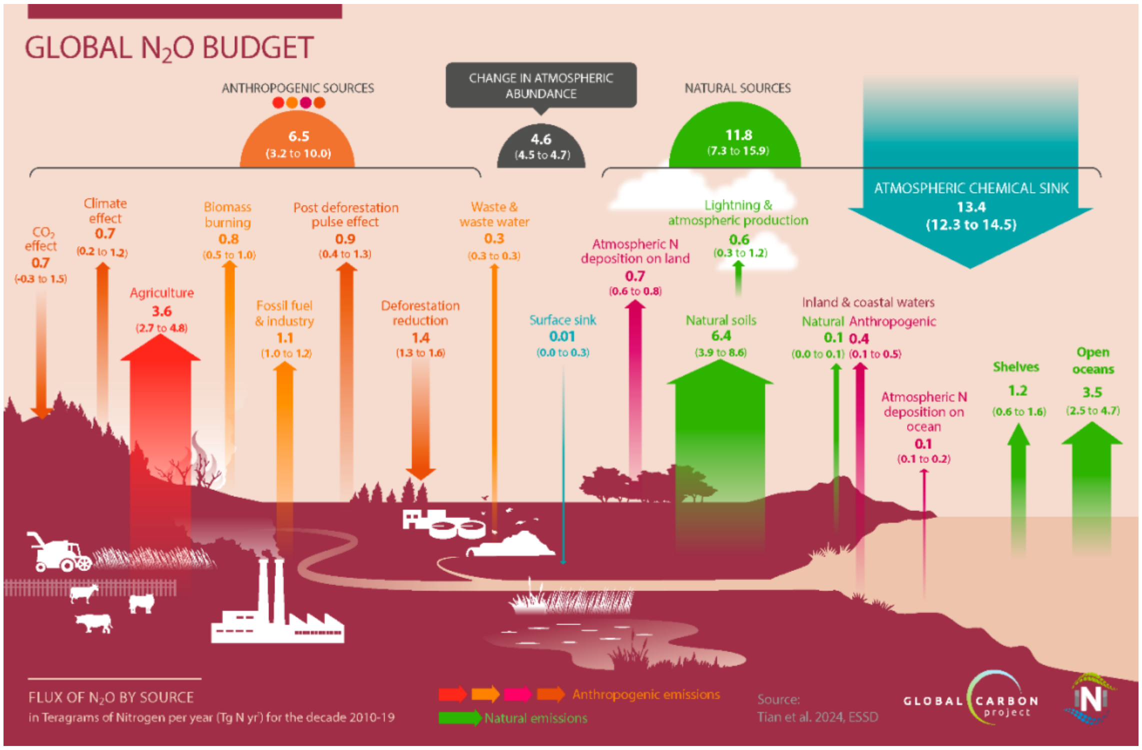
Methane and nitrous oxide, the cycles of which are depicted in Figures 2.3 and 2.4, are two other major greenhouse gases emitted by the agriculture and food sector. Methane from ruminants' enteric fermentation and rice floodings both represent inefficient crop practices. Current and developing technologies are expected to decrease ruminant enteric fermentation and improve manure management while increasing production efficiencies. Similarly, better management and potential cessation of rice flooding will lead to reduced emissions. Consequently, CH_4 and N_2O emissions can potentially be dramatically decreased. These are engineering challenges that are appropriately placed at the top of our collective agenda.

Figure 2.3: Global methane budget 2010–2019



https://www.globalcarbonproject.org/methanebudget/24/files/MethaneInfographic2024.png

Figure 2.4: Global nitrous oxide budget



https://www.globalcarbonproject.org/nitrousoxidebudget/24/files/NitrousOxideInfographic2024.png

3. The Paris Agreement 1.5°C trajectory

The groundbreaking 2018 IPCC Special Report *Global Warming of 1.5°C*[3] sets out compliance requirements for the Paris Agreement:[4]

> *"Limit the increase in the global average temperature to well below 2°C above pre-industrial levels…" and pursue efforts "…to limit the temperature increase to 1.5°C above pre-industrial levels."*

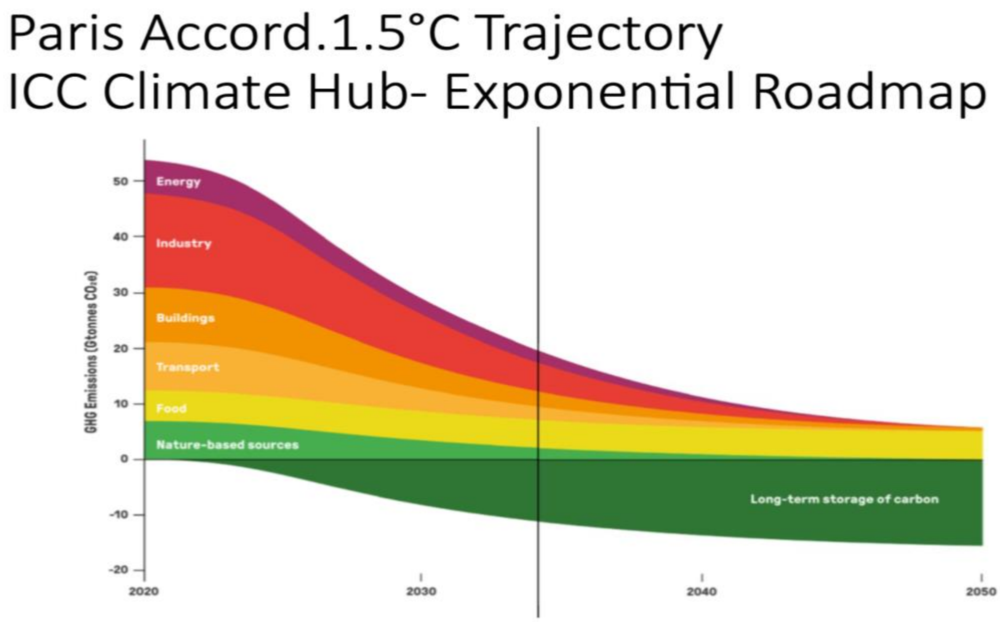
The Special Report, and many others that followed, explain the complexity, challenge and urgency this generation faces.

Less known than the IPC report is the trajectory developed by a UN and private-sector initiative: the Climate Champions' Race to Zero Campaign.[5] This work was initiated in 2020 and is supported by organisations like the International Chamber of Commerce.

Figure 2.5, taken from the Race to Zero Campaign document, summarises the Paris Agreement trajectory and depicts how different sectors must reach zero emissions by 2050 in order to maintain the global temperature within these boundaries.

The yellow stripe shows how food production emissions should remain constant, recognising that its emissions are indispensable for food production. The light green stripe reflects emissions from deforestation and ecosystem degradation, including soil organic carbon losses. All these emissions should transform into long-term stocks of carbon, mainly in soils and biomass.

Figure 2.5: Paris Agreement 1.5ºC trajectory—ICC Climate Hub exponential roadmap



Source: Race to Zero 1.5°C Business Playbook, 2020. https://exponentialroadmap.org/wp-content/uploads/2020/09/1.5C-business-playbook-version-1.1.pdf

In other words, the engineering challenge that ecosystem management implies will improve all aspects of agriculture and food production. These improvements and changes need strong support: not only financial resources from adequately priced negative and positive externalities, but also sound comprehension, limited protectionism, avoidance of politicisation and ideologisation.

4. Agriculture and main emissions sources

As stated above, agricultural activities imply, in many cases, large emissions. Agricultural emissions may be turned from a problem into a solution if adequate engineering technologies are developed and applied.

For example, forest conversion and degradation could be transformed into forest restoration and improvement, activities that could promote employment and regional economic and social development. Similarly, enteric emissions from ruminants could be decreased by implementing anaerobic digestion (AD) for energy and nutrients reuse and other methods that mitigate methanogenic bacteria in the rumen, such as cattle food additives.

These solutions require social approval and the capacity of value chains to transfer monetary resources from consumers and mainly urban stakeholders, who benefit from these improvements, to rural communities that will implement them. The engineering solutions that agriculture could apply to mitigate emissions and sequester large volumes of carbon require financial resources to be transferred from urban societies to rural communities, especially those in developing countries.

The third emissions source in agriculture comes from the use and production of nitrogen chemical fertilisers. Such fertilisers and other nitrogen-rich nutrients must be used prudently, resulting in maximum plant uptake and minimum impact on the environment. This requires more advanced human expertise and technologies than are presently available in many regions of the world. The recovery of nutrients (nitrogen, phosphorus, potassium, zinc, sulfur, etc.) should become a priority to mitigate these emissions and enhance the global carbon cycle and the capacity of ecosystems to sequester carbon in soils and biomass.

5. Agriculture and nature-based solutions

COP21, held in Paris in 2015, was a turning point in the comprehension of agriculture. Before then, it was simply considered an emissions source; a cow was an emitter, like a bus, and a crop was an emissions source similar to a power generation facility.

This comprehension led to a series of initiatives, one of which is the “four per thousand” (or *4 per mille*) initiative. It presented the thesis that increasing agricultural soil carbon content by four parts per thousand (or 0.4 percent) per year would be one of the solutions to mitigate anthropogenic GHG emissions. This may give humanity time to develop and implement energy transition technologies needed to reach net zero emissions while improving agricultural production and ecosystem health.[6]

Shortly after COP21, the International Union for the Conservation of Nature (IUCN) coined the term “nature-based solution,” which they defined as follows:

“Nature-based solutions address societal challenges through actions to protect, sustainably manage and restore natural and modified ecosystems, benefiting people and nature at the same time. They target major challenges like climate change, disaster risk reduction, food and water security, biodiversity loss and human health, and are critical to sustainable development.”[7]

The quantification of the potential of these changes from a GHG mitigation and carbon sequestration standpoint was published in a series of articles starting in 2017.[8]

As can be seen, the potential of these technologies to cope with anthropogenic emissions is large and goes well beyond the emissions generated by agriculture. As was later published in the IPCC’s Special Report on 1.5°C, these solutions are critical to maintaining the atmosphere consistent with the Paris Agreement trajectory.

6. Market challenges

The greatest challenge to the transformation of agriculture from an emissions source into a key solution to the climate crisis is the transfer of resources to those who can apply and manage the best possible engineering solution for each soil, crop or animal species. This applies equally to ecosystems under production and those under conservation.

This resource transfer does not happen naturally, because some human activities have secondary effects beyond their main purpose that are not part of their cost. For example, emitting gases from burning fossil fuels has been a cost-free activity for centuries. Carbon pricing initiatives are very recent and only extend to a small portion of the emissions.

The "polluter pays principle" has been included in all UNFCCC documents since the Río Declaration of 1992, but is difficult to implement. The Paris Agreement, in Article 6, includes two market mechanisms and one non-market mechanism that could support the transfer of resources from those that generate negative or undesired externalities to those that are implementing positive externalities to combat climate change.

Agriculture is a primary sector that can play this vital role in the climate change agenda. However, this is not yet well or widely understood.

7. Engineering challenges

Education and training

As stated in the Strategies section, a new understanding of agriculture and nature is necessary. An important change took place in 2015 during COP21 and continues to evolve, but some outdated ideas continue to affect public opinion and decision-making processes on a global scale.

New technologies and observation capacity

Agricultural technology is experiencing a revolution that converges with other areas of knowledge, including human, animal and plant health, industrial fermentation, organic waste treatment and crop production, etc. The principal change agents are information technology (IT), artificial intelligence (AI), biotechnology, genomics and nanotechnology. Their combination is driving a set of new solutions that minimise chemical use, enhance water-use efficiency, and improve energy and nutrient cycling in the agriculture and food sector.

These AgTech advances, in combination with other fundamentals in biology, physics and chemistry, are the pillars of future production systems. The principal emissions associated with enteric fermentation, rice flooding, chemical nitrogen fertiliser uses, etc. will potentially decrease drastically, while carbon sinks in soils, plants and materials increase.

Living and working in contact with nature requires a keen capacity for observation. These skills are critical for all production systems. The AgTech revolution is also bringing new technologies that enhance observational capabilities. The use of satellite imagery, drones, sensors, etc. is becoming indispensable to the most efficient, highest-yielding production systems. They will enable the development of systems and practices that lead to low emissions and high soil and biomass sequestration.

However, the wide adoption of these technologies is slow, due to several interconnected factors. These include certain subsidies, protectionism and ideological barriers as well as low profit margins and therefore limited capacity for investments in technologies and practices that lead to both productivity increases and emission reductions. Preserving and increasing soil organic carbon is a particularly important challenge that needs addressing, as it will lead to reductions in greenhouse gas emissions and increases in productivity by the agriculture and food sector.

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[5] Climate Champions, "Race to Zero Campaign," accessed June 24, 2024, https://climatechampions.unfccc.int/system/race-to-zero/.
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[8] Bronson W. Griscom and others, "Natural climate solutions," *Earth, Atmospheric, and Planetary Sciences* 14, no. 44 (October 2017): 11645–11650, https://doi.org/10.1073/pnas.1710465114.

3. Oil and gas industry

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The oil and gas industry is a large global industry that mainly provides energy products (principally in the form of liquefied natural gas, gasoline, middle distillates, and fuel oil) to end customers and feedstocks (principally light hydrocarbons and BTX[a]) to other industries.

Transportation, including private, public, commercial, marine and aviation, is heavily reliant on energy products derived from oil and gas. Concerns about climate change resulting from associated greenhouse gas emissions, alternate sources of energy, increased energy efficiencies, and electrification of transportation all make it difficult to predict future demand for the oil and gas industry's products. At present, long-term demand projections vary. However, two matters are clear: First, there will be continued major demand for the industry's traditional energy products in the near term, with the magnitude of demand and changes over longer periods of time difficult to predict;[1,2,3,4] and second, the oil and gas industry will respond to future market demands for new products. This chapter is largely focused on the petroleum refining sector; a section on natural gas and LNG is also included. Oil and gas production and transportation are not addressed.

For the oil and gas sector, the following changes are expected to occur over the mid- to long-term:

- The non-energy fraction of oil and gas consumption will grow at annual rates of about 3 percent, which is higher than the recent industry average for energy products.[5]

- Electrification of transport, especially in the private transport sector, will likely decrease gasoline consumption. This will reduce the refining throughput of catalytic reforming and fluid catalytic cracking units and move their use to aromatics and olefins, respectively.

- There will be a significant reduction in the refinery production of residual fuel oil, enabled by new process technologies.

- New refining feedstocks, such as recyclates and biogases, bioliquids and even biosolids, will be introduced. Co-processing with conventional oil fractions in cracking and hydrogenation units will require significant equipment modifications and hydrogen availability.

[a] Benzene, toluene, xylenes

- Processing units will be needed for the production of synthetic fuels (e-fuels) and new petrochemicals from methane, green hydrogen and CO_2 feedstocks.

This chapter provides insights into the long-term future of the oil and gas industry and presents related strategic actions. Only issues related to emissions resulting from the industry's *operations* are considered here; emissions arising from the use of the industry's *products* are excluded. Such emissions have been addressed in numerous publications, with the 2024 NASEM report providing a comprehensive overview.[6]

Natural gas (NG) and liquified natural gas (LNG) are important subsets of the oil and gas industry. They have special characteristics and broad implications not only for that industry, but also other industries. A section on NG and LNG is therefore included in this chapter.

Hydrogen is also highly relevant to the oil and gas industry and other industries. A separate chapter on green hydrogen and geologic hydrogen was created because they involve technologies that differ significantly from the core oil and gas sector.

Oil and gas

Drivers

The following change drivers were identified and grouped, without indicating priorities.

Non-technical Demographics (population and age distribution) Prosperity Varied national and regional conditions Political stability Climate change objectives and mitigation (including Paris Accord, net zero by ~2050) Energy security, affordability and sustainability Scarcity of fuels (gasoline, diesel, kerosene, etc.) especially for poorer people in developing countries Access to hydrocarbon reserves and resources Markets: size, nature, access Access to capital Regulations Carbon emissions pricing and trading Social acceptance of products and processes Health and safety Expert workforce Research, development, innovation Equity, diversity and inclusion (EDI)
Inputs and feedstocks Hydrocarbons: mainly oil and gas, biomaterials Energy: electricity, fuels, heat Water Recyclates (including plastics/polymers, waste oils)

Products Traditional products (gasoline, diesel (middle distillates), BTX, alkanes (paraffins), asphalts, lubricants, waxes, etc.) and their continued demand Novel/emerging products: alkenes (olefins), H_2 (including geologic H_2) and NH_3 (as energy carriers) Sustainable fuels (especially for aviation)
Technologies Oil refining and gas processing: Electric steam generation Electric steam reforming H_2 and NH_3 production Efficient, low-temperature electrolysers Carbon Capture and Storage (CCS) or Carbon Capture, Utilization and Storage (CCUS) Modular plants, especially for developing regions Improved and new separation processes, except for atmospheric and vacuum distillation Improved and new catalysts Digitisation, artificial intelligence, process simulation Oil and gas transportation and storage: Flaring avoidance Methane emissions reduction H_2 pipelines and storage CO_2 pipelines

Critical uncertainties

The following two critical uncertainties were selected for the oil and gas industry:

X-axis: Trio of sustainability, reliability and affordability (poorly met to highly met)
Y-axis: Availability of advanced technologies (widely available to restricted availability)

Sustainability, reliability and affordability must be viewed jointly. Considering and responding to just one or two of these three drivers is insufficient to understand the future of the oil and gas industry and develop future strategies. The combination of the three drivers is referred to as a trio. It should also be noted that reliability includes accessibility.

Scenarios

Four future scenarios for the oil and gas industry, shown on the next page, result from these two critical uncertainties. Their characteristics are also stated and reflect the detailed change drivers listed above.

Figure 3.1: Scenarios

Advanced technologies: widely available

1. Struggling oil and gas industry
- Trio drivers only marginally satisfied
- Non-technical drivers only partially met
- Feedstocks, energy and water vary in availability and affordability
- Existing and new products only variably accepted, available and affordable
- Technologies for better existing and new products only selectively available and used
- Modern processing, transportation and storage systems for energy products lacking
- Low competitiveness; only some large and regional companies do well
- Poor workforce and innovation capabilities
- Weak EDI

2. Thriving oil and gas industry
- Trio drivers satisfied
- Non-technical drivers met
- Feedstocks, energy and water reliably and affordably available
- Traditional products accepted, available and affordable; declining demand for some
- New products (possibly including geologic H_2) developed, available and competitive
- Existing technologies improved
- New technologies developed and used
- Product transportation and storage issues addressed
- Large and small producers thrive and are competitive
- Strong workforce and innovation capabilities
- Strong EDI

Trio of sustainability, reliability and affordability

Poorly met ←→ ***Highly met***

3. Declining oil and gas industry
- Trio drivers only marginally satisfied
- Non-technical drivers largely unmet
- Variable and unreliable availability and affordability of feedstocks, energy and water
- Products only locally/regionally accepted, available and affordable
- Few new products developed, available and competitive
- Existing technologies improved, but advanced technologies only marginally available and used
- Out-migration from oil and gas industry regions; social instabilities
- Education and innovation systems at risk
- Only a few large companies thrive
- Weak EDI

4. Imperiled oil and gas industry
- Trio drivers satisfied
- Technical drivers only partly met
- Variable and unreliable availability and affordability of feedstocks, energy and water
- Products only locally/regionally accepted, available and affordable
- New products developed, available and competitive
- Existing technologies improved, but advanced technologies only marginally available and used
- Good workforce and innovation capabilities for products, but not technologies
- Companies at risk of becoming non-competitive and takeover targets
- Strong EDI

Advanced technologies: restricted availability

Strategies

To address the future scenarios, four major strategies are proposed. These strategies are applicable to conditions prevailing in all scenarios. They also complement insights presented in the 2022 CAETS Energy Community report.[7] When that is the case (for example, energy efficiency improvements were previously identified), they are not listed as a separate strategy in this report.

Strategy 1: Small modular refineries

A modular refinery is a refinery constructed by integrating skid-mounted modules, each comprising a full processing unit.[8,9,10,11] The modules are constructed off-site and are assembled and tested at the fabrication location before shipping to the refinery site. Transportation issues limit module size, and the capacities of modular refineries are typically small, in the range of 500 to 30,000 bpd.[b] In contrast, most conventional refineries have processing units that are largely constructed on-site and have capacities exceeding several hundred thousand bpd, with some surpassing one million bpd.

When considering small modular refineries and comparing them with large conventional refineries, it is important to ensure that the comparison is performed on an equal basis. Specifically, this means small modular refineries provide products of the same quality (albeit not in the same quantity or diversity) and their GHG emissions meet the same standards as those required for large refineries. In turn, this means small modular refineries have similar processing units to large refineries. Simplifications may occur when small modular refineries process, for example, only sweet crudes that do not require desulphurisation units.

There are no fundamental technical reasons why small modular refineries cannot produce products of the same quality and with the same GHG and other emissions as large, well-functioning refineries, provided appropriate design and operating measures are taken. However, small modular refineries do not benefit from economies of scale. Investment conditions required to make modular refineries viable include proximity and access to crude oil supply, proximity to markets, favourable financing terms, and governmental regulations, incentives and taxation.

The literature on small modular refineries is extensive, mainly highlighting their suitability for developing regions of the world where large refineries are either absent or not well-functioning and where market conditions do not justify large refineries.

The following advantages and disadvantages of small modular refineries are identified:

Advantages

- Capital requirements: Small modular refineries require significantly less capital than large refineries, and small amounts of capital are easier to raise, especially in some developing countries. Large refineries require financing in the billion-dollar range and are typically dependent on international investments, which are often hard to secure. The investment needed to construct several modular plants that serve the needs of multiple geopolitical zones is typically less than the expense of a single large refinery,[12,13,14] and therefore the investment risk potential of small modular refineries is lower.

[b] barrels per day

- Risk profile: Ecologically, modular refineries pose smaller environmental risks in the event of accidents and have less wasted capacity if demand falls, compared with large refineries. Basic environmental protections, consistent with local regulations, can be provided within the context of industrial ethics of developing economies.

- Ease of maintenance: Modules can be easily updated or replaced.

- Scalability and flexibility: Modules can be added, removed or customised as needed, making it easier to adapt to changing requirements and providing flexibility in design and implementation.

- Parallel development: Different teams can work on different modules simultaneously, speeding up the overall development, fabrication and commissioning processes.

- Faster installation compared to conventional (built-on-site) approaches: Modules can be easily transported anywhere in the world and come in a variety of sizes, with capacities typically ranging from 500 to 30,000 barrels per day.[2]

- Scale: Modular refineries and process units can be developed at a scale suitable for electrification of oil and gas operations and for use in biomass processing. The latter typically requires capacities significantly smaller than large refineries due to the dispersed nature of biomass feedstocks.

- Reusability: Modular components can be reused in different projects or systems, saving time and development effort.

- Regulatory approvals: Such approvals are simplified because it is possible, in principle, to get approval for certain types of refinery modules, which eliminates repeated technical approvals for future refineries. Site approvals for constructing modular refineries in specific locations would still be needed.

- Global market: The modular refineries market was valued at $3.2 billion in 2022 and is projected to reach $5.4 billion by 2032.[15]

Disadvantages

- GHG emissions: Even with favourable crude-oil feedstocks, appropriate product slates and typical processing equipment, GHG emissions from modular refineries are the same, on a per-barrel basis, as those of comparable, well-operating large refineries. However, compared with poorly operating large refineries, the emissions from well-designed and well-functioning modular refineries are lower, both in absolute terms and on a per-barrel basis.

- Processing equipment: Normally, large processing equipment, including refinery equipment, is more efficient than small equipment. For example, the heat losses (per barrel of capacity) of a large crude distillation tower are typically less than for a tower with a smaller diameter. However, it is usually possible to overcome the deficiencies technically, though costs may increase.

- Complexity in the development process: Modular design requires careful planning and upfront design to define the interfaces between modules.

- Overhead: Managing large numbers of modules, particularly when provided by different vendors, increases overhead in terms of communication between module designers, configuration management and coordination among teams.

- Dependency management: Interdependencies between modules can make for more complex management of design and procurement, especially when changes in one module affect others and modules are produced by different manufacturers.

- Performance overhead: Modular systems may incur additional performance-testing overhead due to communication between modules, especially in distributed systems.

- Overall cost: Developing a modular system may require more resources upfront compared with singular designs; this can increase total development cost.

- Out-of-country acquisitions: Certain specialised equipment and materials may have to be imported, with adverse impacts on local economies.

- Feedstock transportation: Assuming a refining capacity of 10,000 bpd and crude-oil transportation by tanker truck to a modular refinery (with truck capacity of 20,000L or about 125 barrels), about 80 daily truck deliveries are needed. This is substantial, but also typically insufficient to justify a pipeline.

- Price competitiveness of gasoline and diesel from modular refineries: Large refineries have economies of scale that can undersell modular refineries, thereby putting their economic viability at risk. Government interventions in the form of regulations and incentives may be needed.

- Diversity of processing units: Modular refineries may not have hydrotreating and hydrocracking capabilities, and therefore are either restricted to light, low-sulphur crudes or must secure markets for heavy products.

As an example of the modular strategy in action, two operators in West Texas have received state permits to build small modular refineries, with emissions stated to be roughly 95 percent lower than those from the average Gulf Coast refineries.[7,c] Their particular focus is on feedstocks consisting of light crude petroleum from oil shales.[16,17,18] It was found that such refineries, tailored for light crude and outfitted with new equipment, not only comply with current emissions standards, but also increase efficiency. The West Texas companies intend to capitalise on the opportunity to build refineries domestically from scratch, complete with carbon capture technology.

[c] This claim requires confirmation and likely applies only to certain feedstocks

Some countries have small illegal refineries. Converting them to well-designed, well-functioning modular refineries would have great benefits. Important challenges and prospects associated with making these conversions are described by Angela et al.[19]

In conclusion, the small modular refinery strategy:

- responds to the continuing need for gasoline and diesel (middle distillates) in many developing countries and where it is necessary to reduce environmental risks, where large refineries have performance issues and where very large capital investments are difficult to justify or secure;

- recognises the need for future small modular refineries to be more ecologically sustainable and meet or exceed the performance of traditional large, well-functioning refineries.

Strategy 2: Policies and regulations

Policies and regulations are key drivers and uncertainties for the oil and gas industry, significantly impacting production capacity, capital cost and operating costs. It is essential that policies and regulations allow the industry's products to satisfy the trio of sustainability, reliability and affordability. While policies and regulations will differ, reflecting differences in jurisdictions, they must also recognise that the oil and gas industry is global, integrated and highly competitive. Policies and regulations need to be stable and crafted with both short- and long-term perspectives in mind.

The long-term standing power of policies and regulations is highly dependent on their ability to achieve sustainability, reliability and affordability. Specifically, energy security and affordability are fundamental to modern society's lifestyle, standard of living and economic productivity. It is highly unlikely that policies and regulations designed to achieve ecological sustainability without assuring energy security and affordability will be broadly supported over a long period of time.

While the energy mix is evolving and will continue to evolve, with more renewable energy and possibly more nuclear energy becoming available, oil and gas will likely remain primary energy resources for decades to come. Social pressure is driving commitments from many governments and companies to achieve peak emissions in the intermediate term and net zero emissions in the long term.

The strategic challenge regarding policies and regulations is therefore not only their conceptualisation and coherent implementation, but also ensuring they are widely understood. Public and private organisations, including industry, government and academic institutions, need to collaborate in developing and maintaining this understanding. New and better approaches are needed to bridge the divides that currently exist.

Strategy 3: Emission reductions

Given the continuing need and demand for current oil and gas industry products and the industry's commitments, the principal emissions reduction strategies are:

a. Curtailing fugitive emissions of greenhouse gases, notably methane.
b. Increasing process and operational efficiencies.

c. Implementing carbon capture and storage (CCS) or carbon capture, utilisation, and storage (CCUS).

Implementation of strategies (a) and (b) is well-advanced, based on proven technologies and economics.

The implementation of CCS is a key emission-reduction strategy with great long-term potential. Since CCS is not only pertinent to the oil and gas industry, it is addressed separately in chapter 5.

The development of carbon capture and utilisation (CCU) is another emissions-reduction strategy. However, the products resulting from utilisation and the markets for envisaged products do not yet align well with GHG production from oil and gas. CCU is therefore not addressed in this report.

Strategy 4: New technologies and products

Four principal strategies are envisaged:

a. Electrifying process equipment.
b. Employing hydrogen from low-carbon sources for current and future products.
c. Meeting growing demand for construction materials, solvents, waxes and lubricants.
d. Using artificial intelligence to increase efficiency and productivity.

Electrification of important process equipment, including pipeline compressors, is already occurring, but additional advances will require major technological development and confirmation. Where low-carbon electricity is reliably available at a competitive price, these advances would enable, for example, large electrically powered steam generators, reboilers for distillation columns, preheaters and heaters, and endothermic reactors like methane steam reformers, thereby substantially lowering GHG emissions. Recent papers by Schneider Electric[20] and BASF, SABIC and Linde[21] are addressing electrification of process equipment required for full-scale industrial operations in the oil and gas and petrochemical industries. Long-term reliability and efficacy, maintenance, availability of qualified personnel and cost effectiveness are all issues that require addressing at scale. Safety is an overarching concern. For example, electric heat-tracing that replaces steam tracing is only justified when all safety aspects are addressed.

Hydrogen is traditionally used in the oil and gas industry to upgrade and desulphurise current feedstocks and intermediate products. This use will continue; however, in the future, hydrogen will also be needed to produce new products, including synthetic fuels, especially for the aviation and marine sectors, and feedstocks for new petrochemicals and polymers. At present, the requisite process technologies, including catalysts, have yet to be fully developed for large-scale use.

Hydrogen production with very low GHG emissions is not only important for the oil and gas industry, but also other industries covered in this report. A separate hydrogen chapter has therefore been created.

Demand for construction materials will grow as global populations and prosperity increase. In particular, there will be growing markets for asphalt binders (mainly for roads), solvents, waxes and lubricants. The latter are specialty, high-value products required by a wide range of users and industries. There will also be growing demand for novel plastics that are more recyclable and biodegradable than most current commercial plastics. While these future plastics are unlikely to be made by the traditional oil and gas industry, it will likely provide the feedstocks and thereby undergo a fundamental industrial transformation.

Artificial intelligence is a rapidly evolving technology that can impact the oil and gas industry in a variety of ways, including reducing costs, helping to track and lower emissions and speeding up processes by supplementing human brainpower. AI and machine learning can manage unwieldy data streams using genius-level algorithms, predict when equipment will require maintenance, help optimise CO_2 storage and analyse detailed characteristics of crude oils to predict how they will interact with each other and with equipment, helping to optimise operations.

Natural gas and liquified natural gas

Natural gas in the gaseous and liquid state, designated NG and LNG respectively, is an important contributor to the energy transition. That transition is expected to result in conditions where energy becomes widely and reliably available, at affordable prices, and with minimal net GHG emissions. Several reasons typically support this expectation:[22]

- NG is a large source of globally abundant, reliable and affordable energy and a principal tool in the fight against energy poverty.
- NG is a bridging agent to future green forms of energy by enabling their development with revenues from NG operations.
- NG is a source of net-zero energy when coupled with CCUS.
- NG and LNG infrastructures provide effective starting platforms for clean hydrogen and electricity production.

If NG and LNG operations and uses can be successfully coupled with CCUS, they would not only play a role in the energy transition, but also be part of the end state of that transition.

Important caveats are:[23,24,25]

- energy requirements and GHG emissions (including fugitive emissions) during NG production, processing, transportation and storage;
- energy requirements associated with LNG production, shipping and gasification; emissions due to methane boil-off are a particular concern;
- major NG resources occurring only in a small number of geographic locations, thereby creating potential energy inequities;
- limited CCUS options that meet technical, economic, sustainability and social acceptance criteria, thereby favouring CCS.

This section identifies long-term challenges and opportunities for NG and LNG, based on their fundamentals, concluding with four long-term strategies consistent with the objectives of this report.

NG and LNG fundamentals and comparison with other energy carriers

- The energy density (expressed as J/m^3 at STP) of methane (CH_4), the main NG constituent, is lower than that of all other energy carriers except hydrogen (H_2).
- The energy density of LNG (i.e., CH_4 at –162°C and 1 atm) is significantly higher than that of gaseous CH_4.
- Except for H_2, CH_4 has the lowest CO_2 emissions per unit mass of energy carrier.
- Changing from coal, gasoline, diesel and other heavier hydrocarbons (like fuel oil) to CH_4 reduces GHG emissions per Joule (J) of energy generated. While the reduction resulting from the change is substantial, it does not eliminate GHG emissions unless practiced in conjunction with CCS or CCUS.
- Changing from coal to NG typically results in major reductions of particulate emissions (especially particulates less than 2.5 microns in aerodynamic diameter), leading to major public health improvements.[26]

NG and LNG challenges

Impurities

Raw natural gas in geological formations typically has significant concentrations of H_2O, CO_2, H_2S and light hydrocarbons (such as ethane, propane and other condensates), which are separated to meet pipeline and market specifications. Technologies are well-established to remove these impurities, some of which have significant market value. The exception is CO_2, which requires sequestration or utilisation, challenges addressed in the CCS chapter of this report. Separation and sequestration are energy-intensive and would benefit from significant efficiency improvements. Major work is already underway to address NG impurity issues and energy requirements.

Methane emissions from leaks, venting, flaring and boil-off

Global methane emissions associated with NG production, transportation, and processing arise mainly from leaks, venting, pneumatic controllers and flaring. They are difficult to estimate accurately due to challenges of measurement, distribution over wide geographical areas, large numbers of emitters and variations over time. The International Energy Agency (IEA) reports that global methane emissions associated with the NG industry have been rising over the past decades, amounting to approximately 40 million tonnes per year in 2021.[27] Alvarez et al.[28] indicated that methane emissions from the U.S. oil and gas industry are in the range of 13 million tonnes per year but, more recently and using aerial surveys, Sherwin et al.[29] arrived at 6.2 million tonnes per year for the United States. Similar data from other regions of the world are sparse, but nevertheless suggest significant methane emissions, e.g., for China.[30]

Methane emissions from LNG operations are comparatively small, but this could change as the industry grows. Of particular concern is volatilisation (or boil-off) during LNG storage and transfer.[31]

Effective technologies are available to address methane emissions in most NG and LNG operations with, in many cases, sound economic returns. Specific examples of managing fugitive and vented emissions are given by TC Energy.[32]

Pipeline transportation of NG

Natural gas is usually found in locations far removed from where it is needed, thereby requiring transmission by pipeline over long distances, frequently crossing urban and environmentally sensitive areas as well as rivers, lakes, seas and, in some cases, deep oceans and international borders.

Examples of long-distance land and sub-sea NG pipelines include the North American NG transmission pipeline network (over 900,000 km),[33] West–East gas pipeline in Asia (20,480 km),[34] Yamal–Europe pipeline in Europe (4,196 km),[34] Trans-Saharan pipeline in Africa (4,127 km),[34] ,[d] Bolivia–Brazil pipeline (GASBOL) in the Americas (3,150 km),[34] Rockies Express gas pipeline in the Americas (2,702 km),[34] Nord Stream 1 and 2 (approximately 1,200 km from Russia to Germany)[35,36] and the Langeled pipeline (1,200 km from Norway to the United Kingdom).[37]

The energy requirements to transmit NG by pipeline are, on average, in the range of one to two percent of NG to be transported in North America. However, this is an average figure for the large North American NG system. Energy requirements for specific pipelines depend on physical pipeline dimensions and capacity.[38]

LNG production, transportation and gasification

When large-scale NG transmission by pipeline is not an option due to distance or other reasons, marine transport of LNG may be viable. NG liquefaction followed by LNG storage, loading, marine transport, unloading and re-gasification are established technologies. While safety records are very good, LNG projects are frequently challenged by:

- the time to secure permits to construct and operate NG processing facilities, pipelines, LNG plants, marine loading, shipping and unloading facilities, re-gasification and distribution networks;
- certainty of raw NG price and supply. Typically, very large NG reserves are needed, in the range of 1 trillion cubic feet (Tcf) of CH_4-rich gas for every million tonnes of annual LNG production for 20-year periods.[39] Large LNG plants have nameplate capacities in excess of 10 million tonnes per year;[40]
- raising the associated project capital (often more than US$10 billion), with only very large projects being economically viable.

Comprehensive overviews of the LNG value chain and its economics are presented by Shingan et al.,[41] Baha et al.[42] and Zhang et al.,[43] showing the complexity and need to simultaneously satisfy business, regulatory and technical issues.

The energy requirements to liquify NG are substantial (approximately seven to 15 percent of the LNG feed gas[44]) and fall into the range of 1,500 to 5,100 kJ/kg LNG.[45] Energy requirements to gasify LNG range from 830 to 860 kJ/kg LNG.[46] GHG emissions associated with LNG production have been reported by Zhang et al.[47] and are typically between 0.12 and 0.44 kg CO_2/kg LNG.

[d] In the planning stage and uncertain due to regional instabilities and financing

NG and LNG opportunities

Methane emissions abatement

Reducing methane emissions from leaks, venting, flaring and boil-off in NG and LNG operations presents economic opportunities. For example, Sherwin et al. indicate that the annual methane loss in NG operations in the U.S. is valued at approximately US$1 billion, thereby providing economic incentives.[29] Abatement technologies are available, but their feasibility is site-specific, requires detailed analysis, and cost and technical effectiveness vary with size and intermittency.

Electrification of NG pipeline transmission networks and hydrogen-enriched NG

NG pipelines are primarily equipped with compressors powered by natural gas, but interest in electric compressors is growing, due to their reduced GHG emissions and maintenance requirements. In addition to the availability and price of low-carbon electricity, a key issue is the reliability of electric power supply. Additional issues include capital requirements and the availability of electric compressors. Comprehensive overviews of switching to electric compressors were provided recently,[48,49] indicating the need for improvements but not for radically new technologies.

However, one area merits attention from a long-term perspective: the suitability of materials, equipment and systems handling hydrogen-enriched NG. Hydrogen enrichment, desirable from sustainability perspectives, will likely occur and presents materials challenges for hydrogen concentrations exceeding 10 percent. These challenges are well-recognised and substantial work is already underway, pointing to solutions.[50,51]

Electrification of LNG production

Natural gas is presently the most widely used energy source to liquify NG, with commensurate high CO_2 emissions. However, electricity can also be used and, when available from low-carbon sources, results in significant CO_2 emissions reductions. Freeport LNG in the U.S. uses electric motors instead of gas turbines for compression, thereby demonstrating electricity-based technology on a large scale. However, the electricity supplied to Freeport LNG is derived from fossil fuels.[44]

If the NG supply for LNG plants has significant concentrations of hydrogen, that hydrogen can be used to generate GHG-free power for the liquefaction process.

LNG gasification for electricity generation and other uses

LNG gasification requires approximately 850 kJ/kg LNG. This energy requirement can not only be met by NG combustion, with the formation of CO_2, but also by other means. Potential new opportunities have been summarised by He et al.,[52] Akashah et al.[53] and Wan et al.[54] They include electricity generation by organic Rankin, Brayton, Allam and other thermo-mechanical cycles; air liquefaction and separation; seawater desalination (including freeze and hydrate desalination); cryogenic carbon-dioxide capture; recovery of natural gas liquids from raw NG; data-centre cooling; food processing and preservation; and low-temperature heat storage.

Another potential use of LNG gasification is to reduce the temperature (and increase the pressure) of CO_2 from CCS operations to render the CO_2 suitable for large-scale marine transportation to locations where it may be sequestered in geological formations or otherwise used. Baroudi et al.[55] and Pérez-Bódalo et al.[56] provide comprehensive summaries of the issues pertaining to large-scale marine transportation of CO_2, including the requirement for operations at low temperatures and elevated pressures to ensure that the CO_2 is in liquid or supercritical form.

The new LNG gasification processes, still largely in the conceptual and demonstration stage, have considerable potential as global LNG production increases and GHG emissions from LNG gasification must be minimised.

Chemical reactions with LNG

Chemical reactions of LNG (i.e., reactions at temperatures of –162°C) with, for example, oxygen to form methanol, have not been reported. While the thermodynamics are favourable, the reaction rates under cryogenic conditions are extremely low unless appropriate catalysts are available. To date, no such catalysts have been reported.

However, the conversion of CO to CO_2 has been reported at 120 K (–153°C) using specially prepared gold-titania nano-catalysts.[57] The conceptualisation and search for novel catalysts aimed at converting LNG into commercially valuable products on a large scale are therefore important.

Strategies

Four major, future-oriented strategies that extend beyond the activities currently being pursued are appropriate for NG and LNG operations. Their pursuit will lead to greater availability of affordable energy and improved environmental quality, which in turn will result in better public health.

1. Fugitive methane reduction[e]

- Developing and proving novel and cost-effective technologies for remote detection and prevention of methane leaks and discharges, including discharges from flares and boil-off in LNG facilities.
- Developing and deploying new sensors and sensor systems tied into operational control and management systems.
- Developing standardised and modular approaches for emission collection and processing.

2. Electrification[e]

- Increasing the use of low-carbon (green) electricity throughout the NG and LNG value chains, including compressors, pumps and reboilers, with emphasis on reliability, safety and cost effectiveness.
- Scaling up the production of electricity from LNG gasification using Rankine, Brayton, Allam or other thermal cycles.

3. Novel LNG uses

- Integrating LNG gasification with district cooling and heating systems to provide year-round temperature control for homes, offices and factories, especially in regions with widely varying temperatures.

[e] This strategy is already in the process of implementation in some countries

- Scaling up LNG gasification technologies for novel uses, including air separation, water desalination and food preservation.
- Exploring the production of chemicals under cryogenic conditions, made possible by LNG and novel catalysts.

4. Workforce development

Current and future NG and LNG technologies are inherently complex and sophisticated. They require fundamental understanding and practical experience in diverse fields, including engineering, economics, logistics, regulations and community relations.

Expansion of the current NG and LNG workforces is needed to develop, implement and manage current and new technologies so that they meet market, reliability and sustainability requirements.

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4. Hydrogen

Electrolytic hydrogen	Henrik Lund Frandsen	Denmark
Geologic hydrogen	Dirk Smit	The Netherlands

Hydrogen is widely recognized as an important element in the energy transition and is expected to play particularly important roles in the decarbonization of the industry sectors addressed in this report: oil and gas, chemicals, cement, iron and steel, buildings and smart cities. As an energy carrier and storage medium, hydrogen could also become important for the ICT and data centres sector.[1] Hydrogen's roles in the forestry, agriculture, and food sectors are presently less clear, and its role in the utilization of CO_2 (as part of CCUS and, in particular, e-fuels) awaits the identification of major new products and associated production technologies. The latter are beyond the scope of this chapter.

Given the importance of hydrogen to most chapters and the long-term perspective (>2040) of this report, it was decided to create a separate chapter on hydrogen production that is largely free from greenhouse gas emissions and has the potential to become available in large quantities and at competitive prices. Since comprehensive reviews of hydrogen production are available in the literature,[2,3,4] it was decided to focus on just two technology areas: electrolytic hydrogen and geologic hydrogen.

Electrolytic hydrogen

Various types of electrolysers are already commercially available but, with an increased focus on the energy transition, many more are currently under consideration and development. The primary goal is to raise the efficiency of low-temperature electrolysers (alkaline (AEL) and proton exchange membranes (PEM)) from approximately 77 percent (higher heating value, or HHV) today[5] to as much as 95 percent[6] (cell efficiencies). This increase is important because it lowers the need for renewable energy.

High-temperature solid oxide electrolysis technologies (SOE)[7] are promising. However, their potential efficiency increases are marginal because their system efficiencies already approach 100 percent (HHV).[8] It is primarily the auxiliary components that decrease the efficiency of SOE systems, and this is where moderate efficiency gains can therefore be found. A major advantage of high-temperature electrolysis technologies is the opportunity to integrate heat from downstream processes, e.g., ammonia or methanol production. This can increase their apparent electrical efficiency to 110 percent.[2] Most electrolysis technologies do not currently offer this opportunity, but there is great potential for developments in that direction.

The scaling of PEM technologies is constrained by the need for iridium (Ir),[9] and thus much of the research targets iridium minimization[10] and reuse.[11] In the case of AEL, efficiency increases focus, for example, on reducing site blockage at the electrode/liquid feed interface, separating end products (hydrogen, oxygen),[6] and reducing the activation of the oxygen evolution reaction by increasing temperatures.[12] In SOE research, durability of the fuel electrode is a high priority.[13,14,15] Technologies such as high-temperature proton-exchange solid-oxide electrolysis technologies (SOE-p) are under investigation but, at this stage, commercialisation is still prevented by their poor

Faradaic efficiencies.[16] Anion exchange membranes (AEM) are another low-temperature technology with industrial potential. They are still in their infancy, as they offer moderate efficiencies, but are superior to AEL, for example. Recent research on increasing their lifetime has shown good progress, but the economics are still unfavourable.[17]

In large-scale manufacturing, estimates suggest that only a small fraction (<20 percent for alkaline electrolysers and <30 percent for PEM electrolysers) of the hydrogen cost is due to the cost of electrolysers; it is primarily related to the cost of steel.[5] However, exceptions occur when rare, high-value materials like iridium and platinum are required.[18] Hydrogen electrolysers that rely on rare metals are therefore expected to cover only a small fraction of large-scale future hydrogen demand.

Most scalable electrolytic hydrogen technologies therefore do not differ significantly in capital cost, as they depend on the cost of steel. As with many other technologies, capital cost decreases can be achieved through advanced engineering design and economies of scale.

These insights also suggest opportunities to modify the material composition of electrolyser cells, provided rare and expensive materials are avoided. Cost considerations should always be supplemented by evaluations of sustainability. Technologies relying on platinum and, in particular, iridium will likely inhibit upscaling to meet the needs of large markets. The scarcity of iridium is a critical factor for technologies that rely specifically on this element.[7]

In all cases, the cost of electrolytic hydrogen is heavily dependent on the cost of electricity.

Strategies

Increasing electrical efficiencies

The electrical efficiency of electrolysers and associated equipment is key to decreasing material and land usage and therefore to increasing sustainability. Strategies must focus on low-temperature electrolysers and minimize the use of specialty materials and elements. Research on increasing efficiency is of utmost importance, as large-scale deployment of electrolysers is anticipated.

Operability under fluctuating conditions

Electrolysers must be able to operate under conditions of fluctuating renewable energy supply and hydrogen demand. Research on stable electrodes, stacks and systems that can tolerate fluctuating operations, including electrolyser shutdowns, is urgently needed.

Thermal energy integration

Thermal energy from downstream processes using hydrogen will become increasingly available, and its integration into electrolyser operations will enable major increases in electrical efficiency. Research and long-term evaluations and demonstrations under practical conditions are needed.

Geologic hydrogen

Geologic hydrogen refers to molecular hydrogen (H_2) generated in the Earth's subsurface by abiotic, geology and geochemistry-driven processes. In this chapter we use the term to include both natural geologic hydrogen, which is hydrogen generated and trapped in reservoirs over geologic time (somewhat analogous to hydrocarbon reservoirs) and engineered or stimulated hydrogen, which is hydrogen generated in situ through targeted subsurface interventions (e.g., water/brine injection and associated permeability and thermal management).

The field of geologic hydrogen is developing quickly, but there remain important and, in particular, production engineering questions regarding its potential relevance at industrial scale. Progress requires more experiments and pilot field data, as well as regulatory pathways that enable responsible exploration and pilot testing.

Although geologic hydrogen is presently still relatively unknown and not well understood, interest is quickly rising as its potential to become a large-scale, low-cost and low-emission chemical building block and energy vector becomes clearer.

Hydrogen can also be present in subsurface systems involving organic matter, mainly from fossil hydrocarbon accumulations. These occurrences are outside the scope of this chapter, which focuses on abiotic geologic hydrogen, which involves production processes that have manifestly (ultra) low greenhouse gas emissions.

Chemically and physically, geologic hydrogen is identical to hydrogen produced by any other route, but its purity may vary when produced in a reservoir. For stimulated production, high levels of purity seem very feasible.

Comprehensive review articles on geologic hydrogen, including its origin, occurrence, and commercial potential, have been published by Truche and others,[19] Ellis and Gelman,[20] Zhang and Li[21] and, very recently, Moradi and others.[22]

This section aims to provide a concise overview and highlight priority strategies to assess its possible industrial relevance, leading to three important strategies for future work.

Where is geologic hydrogen found?

Onshore hydrogen vents are relatively widespread on all continents, and some have been known to humanity for millennia. They are usually low-flux seepages, often mixed with other gases like methane and, in some cases, coexisting with helium. Sites with geologic hydrogen potential are shown in Figure 4.1. Since the late 1970s, hydrogen has also been documented in some offshore hydrothermal vent systems near mid-ocean spreading centres, where hydrogen is co-produced and fluxes can be orders of magnitude higher.

Systematic exploration for natural hydrogen only started in recent years (see Figure 4.2). This is partly due to the ubiquitous distribution of seepages. Recent studies indicate that the global continental hydrogen production rate is on the order of 500,000 tonnes/year.[23,24] This is, in fact, a fast geological production rate when compared with the generation rate of fossil hydrocarbons in a source rock, which is orders of magnitude lower. (The source rock expulsion rate into a sedimentary basin is, in fact, comparable to the hydrogen generation rate.[25,26]) Given that hydrocarbon generation is about 500 million years old, while hydrogen is generated for much longer periods (at least 2 billion years), work by the United States Geological Survey (USGS) suggests hydrogen reserves may be adequate to meet demand for thousands of years, even with low recovery factors.[20,27]

However, and perhaps paradoxically, at present there is only one known natural hydrogen field in continuous commercial operation, i.e., flowing hydrogen to the surface at the well head. It is in Bourakebougou, Mali (West Africa) and produces enough hydrogen to power a generator that supplies a local village with electricity.[28,29] The flow rate at the well head is reported to be 135 kg H_2/day[30] and cost estimates are understood to be less than US$1.00/kg of H_2. This flow rate is believed to be too low for wide commercial use, which is assumed to require roughly 2–3 tonnes per well per day (at a cost of US$1.00/kg).

Current knowledge regarding geologic reservoir distribution, reservoir geology and size, and in particular reservoir producibility, is still in its infancy, somewhat similar to the early days of oil and gas exploration. However, thanks to decades of developing engineering geosciences, enabled by huge increases in affordable digital and computing technologies, hydrogen exploration can be leveraged and may develop much faster. For example, more comprehensive subsurface data mining and re-examination of legacy subsurface data (often acquired for different purposes) has allowed the identification of numerous hydrogen seepage sites that were previously disregarded.

Yet detailed subsurface conditions conducive to the formation and accumulation of natural hydrogen differ markedly from their oil and gas counterparts, and the appropriate knowledge remains to be developed. Many of the sites where seeps have been reported, shown in Figure 4.1, should therefore be regarded as *initia*—potential exploration prospects requiring detailed work.

Figure 4.1: Map of hydrogen detections ("shows") in various environments at concentrations >10 percent vol.[23]

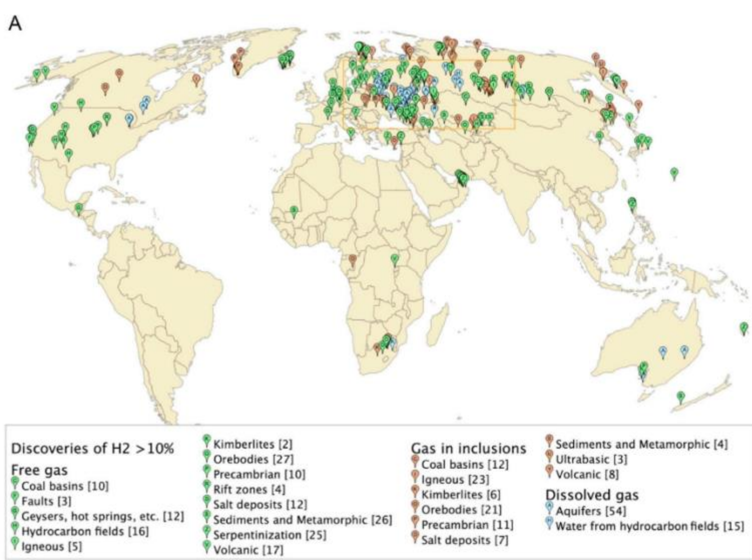

Figure 4.2: Selected geologic hydrogen projects globally

*Source: Rystad Energy's Hydrogen Solution; March 2024
A Rystad Energy graphic

https://www.rystadenergy.com/news/white-gold-rush-pursuit-natural-hydrogen

These developments have led to significant growth in the number of early exploration licenses issued for exploration wells to companies like Gold Hydrogen in Australia, HyTerra and Koloma in Kansas, USA, and Helios Aragón Exploración in the Aragon–Pyrenees region of Spain.

In 2024, over 40 companies, mostly start-ups, were known to be searching for geologic hydrogen. This number is up from just 10 in 2020. Currently, the number may be approaching 100, exploring primarily in Australia, the United States, Spain, France, Albania, Colombia, South Korea, Thailand and Canada.[31]

However, at present, there are no published well tests or production rates at the well head. This suggests that formation and, in particular, producibility of these “hydrogen reservoirs” may be much more difficult than, for example, hydrocarbon reservoirs.

How is natural geologic hydrogen formed?

Unlike conventional oil and gas, which are formed by the anaerobic conversion (cracking) of plant and animal matter, geologic hydrogen is believed to result mainly from two types of inorganic reactions: radiolysis and the chemical reduction of water.

Radiolysis occurs when radioactive elements like uranium, thorium and potassium, which are typically present in the Earth’s mantle, decay and form decay products that include alpha particles, beta particles, or gamma rays. These decay products, when sufficiently energetic, can split water into hydrogen and oxygen by processes known as radiolysis. The oxygen may combine with water to form hydrogen peroxide. The fate of the latter depends on the presence of other constituents and is still largely unknown. Hydrogen peroxide is an important oxidizing agent that undergoes further reactions, including recombination with hydrogen. Radioactive decay can also result in the formation of other elements, for example helium, and the joint occurrence of hydrogen and helium may suggest that the hydrogen formation is due to radiolysis. Joint occurrences have been observed, for example, in Australia, South Africa, and the United States.

Radiolysis of water is a (slow) process occurring at great depths. It is therefore only commercially relevant when the geologic hydrogen is trapped for millions of years and at accessible drilling depths. The role of water radiolysis in the production of geologic hydrogen at commercially relevant scales is still unclear, but could be significant.[23]

Chemical reduction of water denotes abiotic chemical reactions that occur when rock systems rich in ferrous iron (Fe^{++}) come into contact with water. The water is reduced to hydrogen, and the oxygen oxidises the metallic rock constituents. These reactions are mostly (sometimes highly) exothermic. In contrast, most large-scale, industrial hydrogen production processes, such as steam methane reforming and water electrolysis, are mildly to highly endothermic.

A known class of subsurface reactions producing geologic hydrogen is **serpentinisation** involving oxidation of Fe^{++} in olivine-rich formations. Olivine is an iron-containing mineral occurring frequently in a so-called ultramafic host rock, such as peridotite. When olivine comes into contact with water, hydrogen can be produced as a byproduct. Many other minerals can also react with water and produce hydrogen. Examples are dunite and harzburgite, which are also reasonably widespread. The host rock containing these minerals, although of mantle origin, is often emplaced at accessible depths by tectonic processes (e.g., seafloor spreading, ophiolite obduction, and major fault systems). In particular, at seafloor spreading centres like mid-ocean ridges, seawater circulation and elevated temperatures can drive rapid serpentinization (often near ~300°C). In continental settings, temperatures are typically lower and water access can limit rates; near-surface weathering and oxidation can also reduce accessible Fe^{++}, so sustained generation and trapping reservoirs are typically only plausible at depth.

Ultramafic rock (containing less than 45 percent by weight of silicates) such as peridotite is not the only source of geologic hydrogen formation: mafic rock formations (containing between 45 and 55 percent silicates), which are more widespread, can also form hydrogen upon reaction with water. Banded iron formations (BIF) and other iron-rich sedimentary or volcanic units are potentially important examples: although their Fe^{++}/Fe^{+++} ratios may be low, their total iron content can be high and hydrogen generation has been reported upon water–rock interaction. This has suggested hydrogen prospectivity in and around iron-ore provinces and mines (e.g., Australia, Brazil, Namibia and South Africa). Furthermore, these formations are relatively widespread over all continents. However, the efficiency of hydrogen formation and then production is more poorly quantified and understood. Hence, for clarity, the discussion below focuses on serpentinization in olivine-rich ultramafic systems, which are comparatively well-studied.

Olivine is a solid solution of magnesium–iron silicates with the general formula $(\underline{Mg},\underline{Fe})_2SiO_4$. The solution ranges from pure iron silicate (Fe_2SiO_4) to pure magnesium silicate (Mg_2SiO_4), called fayalite and forsterite respectively. Typically, the ratio of iron to magnesium is 1 to 9. Furthermore, the ferrous content is about 12 percent by weight. While it is not the highest-known ferrous iron-containing mineral, olivine and its structural variants constitute over 50 percent of the Earth's upper mantle and form its most common minerals by volume.

In natural settings, olivine is part of a peridotite "host rock" that usually also contains pyroxene minerals having the general formula $XY(Si,Al)_2O_6$, where X represents calcium (Ca), sodium (Na), iron (Fe(II)) or magnesium (Mg) and, more rarely, zinc (Zn), manganese (Mn) or lithium (Li). Y represents metal ions of smaller size.[a]

Although olivine and pyroxenes both contain ferrous iron (Fe^{++}) that, when exposed to water under suitable conditions, can be oxidised to ferric iron (Fe^{+++}) with the formation of molecular hydrogen, the direct involvement of pyroxenes is less straightforward compared to olivine. In fact, pyroxenes can influence hydrogen production indirectly, as they affect the overall reaction environment in peridotite. The simplest and most studied process involves the ferrous component in olivine, which is fayalite. For fayalite, the overall reaction is:

$3Fe_2SiO_4$	+	$2H_2O$	=	$3SiO_2$	+	$2Fe_3O_4$	+	$2H_2(aq)$
fayalite		water		quartz		magnetite		hydrogen

The magnesium-containing part of olivine, forsterite, serpentinises via a similar equation, but does not lead to the formation of hydrogen:

$4Mg_2SiO_4$	+	$4H_2O$	=	$2Mg(OH)_2$	+	$2Mg_3Si_2O_5(OH)_4$.
forsterite		water		brucite		serpentinite

Forsterite also reacts with the quartz formed from fayalite to water and serpentinite. This is important for balancing the overall reaction:

olivine + water = serpentinite + brucite + magnetite + hydrogen

The purpose of these simplified equations is to show that:

- hydrogen is formed, in essence, as a by-product when olivine contacts water, which may be in the form of brines;
- hydrogen is formed by oxidising iron from the ferrous (Fe^{++}) state in olivine to the ferric (Fe^{+++}) state. This is also generally true for many ferrous iron-containing minerals in mafic formations. However, they have received less attention;
- water acts as an oxidising agent and is consumed in the reactions. Stoichiometric calculations indicate that 180 litres of water are required to produce 1 kg of hydrogen from about 1,000 kg of olivine (or 0.3 cubic metre). This water is taken up by the reaction product, a rock called serpentinite, which is very different from the original olivine: it is densely fractured and, correspondingly, its density is about 30 to 40 percent less. Hence, serpentinisation leads to (rock) volume increases. Such fractures have been observed in many thin sections of serpentinised or partially serpentinised olivine rock. The dense fracture network, together with the reaction's exothermicity, allows water to further react with fresh olivine. As a result, the reaction self-propagates until all the olivine is fully consumed, provided access to enough water is maintained.

[a] Mainly chromium, aluminum, magnesium, cobalt, manganese and, to a lesser extent, scandium, titanium and vanadium. See also the Wikipedia page on olivine: https://en.wikipedia.org/wiki/Olivine

The reactions occur naturally in actual rock systems, as water migrates by gravity or interfacial tension through existing fractures and fissures, allowing it to come into contact with olivine. However, the chemistry is, in reality, more complicated than the above equations suggest, involving numerous intermediate steps and influenced by varying kinetic, equilibrium, pH, temperature, and pressure conditions. Hence, understanding the thermodynamics of actual reaction processes is still the subject of active research and highly relevant in production engineering. Frost and Beard provide a comprehensive overview of serpentinisation reactions, including the role of pyroxenes.[32]

As mentioned earlier, serpentinisation of olivine is highly exothermic, yielding about 120 MJ of thermal energy per kilogram of H_2 produced. Under adiabatic conditions, this would lead to a temperature rise in the olivine of about 140 degrees Kelvin!

This strong exothermicity creates significant thermal stresses, which further reduces the fracture density. The resulting fracture networks may increase permeability and hence accelerate the generation of hydrogen. Therefore, an important question arises: is it possible to engineer an in-situ hydrogen generation and production process? This may have advantages, as it reduces the need for a geological trap which, in many cases, is much less widespread than the hydrogen source rock. The concept of stimulated hydrogen is to deliberately introduce water into olivine-rich rock with the intent of forming hydrogen. It only requires a significant amount of source rock (e.g., olivine) at accessible and affordable depths and in a temperature range optimal for serpentinisation.

How can geologic hydrogen be produced commercially?

It is now clear that the physics and chemistry of hydrogen formation are very different from hydrocarbon formation and that they imply important differences in reservoir geology and production processes. Unlike hydrocarbon generation, the much higher hydrogen formation rates offer an opportunity to produce hydrogen in situ, in a fully engineered brine circulation system optimized, for example, for ultramafic source rock formations. Thus, in principle, there are fundamentally two approaches to the production of geologic hydrogen on a large commercial scale:

- **Natural (i.e. historically trapped) geologic hydrogen:** finding and producing accumulations that have developed over long periods of time. In practice, this involves mapping hydrogen-generating rocks (ultramafic/mafic units, iron formations, and locally radiogenic basement) and migration pathways, and then locating traps and seals where hydrogen may have been retained and can now be produced at high enough rates to be commercially attractive. Development of new exploration technologies, possibly adapted from those developed for oil and gas exploration, may be successfully leveraged, according to Mathur.[33]

To frame exploration opportunities, one may borrow a process called "play-based exploration," developed and matured in the hydrocarbon exploration industries over several decades. It provides a practical logical framework to methodologically de-risk exploration opportunities with chemical and geophysical data inputs. Examples include the use of analytical techniques to test for hydrogen and associated gases such as helium that are indicative of geologic hydrogen formation due to radiolysis. Although the geology is truly different from hydrocarbon geology, the exploration processes are conceptually similar. Adaptation of known geophysical hydrocarbon exploration techniques is certainly feasible, but is still rather immature. Increasingly, geophysical data such as seismic and potential field data (gravity and magnetic data) may be used in a quantitative interpretation process, which bears many similarities to hydrocarbon exploration technologies.

However, there are also important differences: hydrogen residence times in the subsurface, unlike for hydrocarbons, are severely impacted by microbial activity. Furthermore, the high reactivity of hydrogen in carbon- or sulphur-rich environments can produce, for example, methane and hydrogen sulfide, which may reduce hydrogen accumulations significantly over geologic time. Recent studies by Prinzhofer and Cacas-Stentz[34] suggest that the longevity of hydrogen in traps can be orders of magnitude smaller than that of hydrocarbons. This implies that reactive transport phenomena related to hydrogen flow from the generation zone to a reservoir, thus the microbial consumption of hydrogen, as well as seal integrity and quality over geologic time, are much more critical for hydrogen reservoir integrity than they are for hydrocarbon reservoirs.

- **Engineered (stimulated) geologic hydrogen:** locating reactive ferrous-iron-bearing formations and deliberately stimulating in situ hydrogen generation. This would typically be done by enabling controlled water or brine access (and, where needed, managing permeability and temperature) with the intent of sustaining hydrogen generation and deliverability at commercially relevant rates. The main challenge is to create and sustain rapid growth of reactive surface area in the hydrogen source rock (e.g., olivine) by mechanical and optimally chosen brine chemistry. This is a demanding challenge because the stimulated hydrogen formation must be faster than typical natural rates, controlled, and result in producible hydrogen at sufficiently high pressures to be commercially relevant. The reaction rates of serpentinisation at ambient temperatures are low and may require initiation by the provision of heat. Production strategies can, however, leverage the creation of thermal stresses caused by the reactions. This enables further growth in the micro-fracture network. This approach is rapidly becoming an active field of research in hydrogen-based reactive transport science and engineering.

These approaches each pose different challenges, but they also share a critical need to understand hydrogen flow in fractured rock formations, as well as reactive transport phenomena impacting movement of hydrogen to the surface.

Strategies

Geologic hydrogen, either found by exploration or produced by stimulation, requires much greater understanding, in particular of production engineering and the underlying science, before it reaches wide commercial and regulatory acceptance. That understanding, in turn, requires much more field, laboratory, and simulation data than are currently available. Many companies involved in the geological hydrogen field are start-ups with limited staff and financial resources to do even basic work, including reviews of historical field data focused on other resources. The role and funding of governmental agencies is therefore important. Similarly, specific regulations are missing in many jurisdictions, thereby impeding authorisations for exploratory and even small-scale field work, which are necessary precursors for commercial production.

Four strategies are suggested:

1. **Develop comprehensive understandings of geologic hydrogen formation processes under field conditions.**

   The chemistry and physics of geologic hydrogen generation by radiolysis and water reduction (including serpentinisation) need to be determined under conditions representative of deep and low permeability systems. Both hydrogen and helium formation processes must be addressed to establish their relative importance. In turn, this will guide commercial evaluations and development of geologic hydrogen.

2. **Conduct fundamental laboratory and modelling studies**.

   This work includes small-scale studies on radiolysis, serpentinisation, and other reactions, subsurface geologic hydrogen flow and reactions, and rock mechanics to provide sound understanding of the relevant phenomena and their relative importance.

   Geochemical analytical techniques, drilling and completion technology, and exploration (geophysical) techniques need to be developed and tested with a specific focus on geologic hydrogen. Much of this work can be accelerated by modelling studies in conjunction with small field-scale demonstration projects, possibly involving large mining and perhaps oil and gas industries.

3. **Perform economic and sustainability studies on geologic hydrogen.**

   Economics and sustainability will ultimately determine the commercial viability and acceptability of geologic hydrogen production and use. Requisite studies and results are essential to guide laboratory, modelling, and field work. The results are also essential to gain acceptance and support from decision-makers, investors, and the public. Some initial studies are available, but site-specific information is still largely missing.[35,36]

4. **Create expertise to assess, develop, and operate commercially viable geologic hydrogen projects.**

   Present expertise is fragmented, thereby calling for:

   - Science and engineering programs at universities that create integrated expertise in the geosciences of mineral-based resources (from mafic and ultramafic geologies) with chemical engineering of brine circulation and energy resource production and storage systems. For example, the chemistry (thermodynamics and kinetics), reactive transport, and characterisation of brine-rock interfacial processes (often far from equilibrium and in highly reducing environments) are insufficiently understood, especially under non-equilibrium, elevated temperature, pressure, and reducing conditions typical of subsurface environments. Such integrated programs would also address the utilisation of subsurface brine chemistries for energy recovery based on mineral conversion and storage processes, potentially leading to much smaller footprint alternatives in surface engineering.

- Cross-industry field and pilot projects focused on geologic hydrogen, supported by government and involving the mining, oil and gas, and geothermal industries. Such projects would lead to the development of a wide range of important skills in project engineering, new business models, and a clear vision of how these industries can jointly contribute to the energy transition based on geologic hydrogen.

- Clear and stable government regulations governing all aspects of exploration for and production of geologic hydrogen. In the case of the European Union, the relationship to the Taxonomy for Sustainable Activities must be made known.

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5. Carbon capture and storage (CCS)

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This chapter provides an overview of CCS. It should be read in conjunction with the industry chapters in this report.

Introduction

The pathway to net zero by 2050, as identified by the International Energy Agency (IEA), includes a major decline in the share of fossil fuels in the global energy mix from 80 percent (energy supply of 587 EJ from all sources) in 2020 to just over 20 percent (energy supply of 543 EJ from all sources under a net zero scenario) in 2050.[1] What remains of fossil-fuel use in 2050 would be paired with carbon capture, use and storage (CCUS). In cases where practical and technical difficulties make it impossible to eliminate emissions in certain sectors, including hard-to-abate industries, these emissions must be balanced by removing an equivalent amount of CO_2 through carbon dioxide removal (CDR), such as nature-based or technology-based solutions.[1] Currently, the vast majority of CO_2 being removed is via biological means (some 2 Gt of CO_2 per year from trees and soils) but increasingly there are concerns that some of these nature-based solutions only provide short-term storage. Biological means will not be considered further in this chapter.

Carbon capture and storage (CCS) holds considerable strategic value as a climate mitigation option in the transition of the global energy system toward net zero emissions, not least because geological storage is permanent.[2] Currently, while the main application for CCS is to reduce emissions from existing energy assets, it is increasingly recognised that CCS also has an important role to play in decreasing emissions from other sectors. These include hard-to-abate industrial sectors such as steel and cement. Additionally, CCS-based technologies such as bioenergy with CCS (BECCS), waste energy with CCS (WECCS), hydrogen production from natural gas coupled with CCS, and direct removal of CO_2 from the atmosphere coupled with permanent geological storage are receiving increasing attention.

In addition to storing carbon dioxide via CCS, it is also possible to use CO_2 as a raw material in industrial processes by contributing to the replacement of fossil fuels (for example, in the production of clean aviation fuels) and chemicals, and in the production of completely new and valuable products like plastics and building materials such as high-CO_2 cements. This is referred to as carbon capture and utilisation (CCU). This chapter will not consider the utilisation of CO_2 further; however, details on these technologies are available.[3]

The IEA projects that CCS technology will contribute around 8 percent of the necessary emissions reductions needed to achieve net zero emissions by 2050, ranking it third after renewables and energy efficiency.[4] To meet this goal, CCS must capture and sequester some 6 Gt of CO_2 annually by 2050. In 2024, the amount of CCS captured and sequestered was approximately 50 Mt of CO_2 per year;[5] this is about 1 percent of what is needed. The GCCSI estimates that the CCS facilities currently under construction will increase this by 100 MtCO_2 per year and that a large number of projects are at the proposal or planning stages. Nonetheless, both the shortfall in available CCS capacity and the future need are substantial and represent a major challenge. The IEA's Greenhouse Gas Research and Development Program has identified the need to create 70–100 new capture facilities per year worldwide. The London Register of Subsurface CO_2 Storage recently reported that CO_2 geologically stored by CCS since 2006 was approaching 400 Mt.[6] However, current CCS deployment rates (the majority associated with natural gas processing and enhanced oil recovery (EOR))[7] constitute only a small fraction (nominally 10 percent) of the required CO_2 storage needed by 2050.

In the case of technology-based CDR solutions, two technologies that are increasingly deployed in Europe involve combining CCS with bioenergy derived from biomass (BECCS) or from municipal waste (WECCS). In the USA, CCS is being very successfully deployed to mitigate CO_2 emissions for ethanol production. Work is underway on the production of synthetic fuels using DAC (Direct Air Capture) derived CO_2. While direct air capture with CCS (DACCS) is currently only deployed at a pilot or demonstration scale, it is receiving increased attention from high-value companies wishing to purchase durable carbon offsets. While these technologies only currently sequester some 40 Mt of CO_2 per year in total, the IEA has estimated that to achieve net zero emissions by 2050, they must be increased to 2.4 Gt of CO_2 per year,[8] of which 1.9 Gt of CO_2 per year is permanently sequestered and 0.5 Gt of CO_2 per year is used for alternative purposes, such as synthetic fuels. Technology-based CDR is discussed later in this chapter.

The IEA has used industry analogues to assess whether the required build-out rates for CCS implementation, based on their estimated need for 70–100 new capture facilities per year worldwide, are feasible. They considered the logistics of five aspects of CCS that require accelerated implementation. Their assessment found that while storage site discovery will likely be adequate and technological roll-out should be achievable based on analogous industries, maintaining that growth might be more difficult. They estimated that it may take up to 10 years to develop a geological storage site, including de-risking the site, data gathering and analysis to prove its viability and general acceptance.[9] However, this is based on greenfield sites and could be significantly reduced for brownfield sites, such as depleted oil and gas fields.

The cost of capturing CO_2 can vary significantly, mainly depending on the concentration of CO_2 in the gas stream it is being captured from. For example, the estimated levelised cost of separating CO_2 contained in high-concentration streams can be as low as US$15 to US$25/t of CO_2. For more dilute CO_2 streams (e.g., flue gas from power plants), the cost of CO_2 capture ranges from a minimum of US$40 to more than US$100/t of CO_2; capture represents around 75 percent of the total cost of CCS when applied to power production. The levelised cost for direct air capture (DAC) is estimated to range from an optimistic US$130 to more than US$300/t of CO_2.[10]

Achieving higher levels of carbon sequestration will rely on rapid and significant scaling-up of CCS. CDR has been much slower than originally projected. The potential of CCS to mitigate climate change has been recognised since the 1990s, but deployment has been slow. There are several reasons for this. The original focus on large-scale deployment of CCS for mitigation of emissions from coal-fired power generation was replaced by the wide-scale introduction of natural gas and low-cost renewable energy. Also, the high cost of CCS was seen to compare unfavourably with purchasing low-cost, nature-based carbon offsets. However, in recent years, and particularly since the adoption of the Paris Agreement in 2015, it has become evident that durable nature-based offsets are increasingly expensive and limited in their availability.[11] This, in turn, has perhaps made the cost of CCS more acceptable, particularly in the USA, because of a (until recently) favourable tax regime for CCS, and in Europe through significant financial assistance from the European Commission. In addition, some major companies are increasingly willing to pay a significant premium for the type of permanent storage that CCS, DACCS, or BECCS can offer. However, technological developments described below, cost reductions and efficient and safe deployment, together with community acceptance, remain crucial to the large-scale uptake of CCS-type technologies.

Technology readiness level

The capture, transport and storage of CO_2 as a successful mitigation strategy hinge on the availability of technologies at each stage of the process. One way to assess where a technology is on its journey from laboratory to marketplace is to use the technology readiness level (TRL) scale.[a] Several CCS technologies are widely deployed today and are classified at TRL9, Commercial. These include the following: CO_2 capture via chemical absorption in coal-fired power plants and from natural gas with high CO_2 concentrations, CO_2 transport via pipelines; injection of CO_2 for enhanced oil recovery (EOR); and CO_2 capture from biogas using membrane or adsorption technologies. Other applications, including DAC (using both solid and liquid solvents), are at the Lab-scale Plant/Pilot Plant stages (TRL5 and 6), while CO_2 capture from cement and iron- and steelmaking ranges from Lab-scale Plant/Pilot Plant through to Early Commercialisation stage (TRL8). Other technologies at the Demonstration stage (TRL7) include CO_2 capture via chemical absorption in both gas-fired and biomass (BECCS) energy generation. Although recent commercial deployment of BECCS is still modest,[12] it may be reaching possible TRL 8 in some northern European locations.[13] CO_2 capture from biogas using membrane or adsorption is presently at TRL9.

In the sustainable development scenario presented by the IEA, nearly 60 percent of the cumulative emissions reductions from CCUS through to 2040 is expected to come from technologies that are currently at the prototype or demonstration stage. Further, these technologies still require major improvements. The other 40 percent come from technologies that are already mature or at the early adoption stage and can be scaled up rapidly, bringing forth incremental technological improvements and cost savings.

Carbon capture and storage[b]

The following sections of this chapter explore systems for CO_2 capture from flue gases (pre-combustion capture, post-combustion capture, and oxy-fuel combustion);

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[a] The traditional technology readiness level (TRL) scale ranges from TRL1 (Concept) to TRL5 (Laboratory-scale Plant), and then TRL6 (Pilot Plant), TRL7 (Demonstration), TRL8 (Commercial Refinement Required) and TRL9 (Commercial). This chapter will consider only those technologies that have progressed beyond the laboratory and are currently at stages TRL6 to TRL9.
[b] Unless otherwise noted, the remaining text draws from Bartosz Dziejarski, Renata Krzyżyńska and Klas Andersson, "Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment," *Fuel* 342 (June 2023). For a comprehensive source of information and data on CCS, refer to the Global CCS Institute: https://www.globalccsinstitute.com/.

summarise CO_2 separation methods (absorption, chemical looping combustion, adsorption and membranes); consider CO_2 transport via various means, including pipeline and ship transport; evaluate various CO_2 storage methods; and characterise both BECCS and WECCS as innovative connections of biomass energy production with CO_2 capture and direct air capture (DAC).

CO_2 capture systems

There are three main methods of capturing CO_2 that can be implemented in power plants to obtain a concentrated stream of CO_2 from fuel combustion. These are pre-combustion capture, post-combustion capture, and oxy-fuel combustion. Capture systems are also required for industrial process streams (e.g., iron and steel, cement and chemicals).

Pre-combustion capture

Pre-combustion CO_2 capture technology converts solid coal fuel or petroleum residues (heavy oil fractions) into gaseous fuels at high pressure. This gas is then converted primarily to hydrogen and CO_2 via the water–gas shift reaction. The CO_2 is usually separated by chemical absorption. Pre-combustion capture is a mature technology (TRL9). Some advantages, opportunities, disadvantages and challenges of pre-combustion capture are set out in the table below.

Table 5.1: Advantages and disadvantages of pre-combustion capture

Advantages or opportunities	Disadvantages or challenges
• Used extensively in the industry sector • Achieves 92–93 percent CO_2 recovery • Requires less energy for CO_2 separation and compression steps—high CO_2 concentrations and partial pressure (<50 percent of post-combustion capture)	• Energy requirements are significant compared with post-combustion capture method since energy is required for the reforming process and air separation • Improvements to efficiency of energy recovery remain to be achieved • Requirement for a chemical plant upstream of the power turbine • Retrofitting existing facilities increases the cost and complexity, thereby presenting difficulties for commercialisation

Post-combustion capture

The key purpose of post-combustion capture is to capture and separate CO_2 following the removal of other products contained in the flue gas mixture, such as sulphur dioxide and nitrogen oxides. Post-combustion capture is a mature technology (TRL9) when used in power plants with aqueous amines for separation. Amines are also used to remove CO_2 from natural gas containing high levels of CO_2. When used in the steel industry, post-combustion capture is at the TRL6 level, Pilot Plant Demonstration.

Important advantages, opportunities, disadvantages and challenges of post-combustion capture are provided in the table below.

Table 5.2: Advantages and disadvantages of post-combustion capture

Advantages or opportunities	Disadvantages or challenges
• Applicable to new and existing coal-fired power plants • Higher thermal efficiency for conversion to electricity than pre-combustion methods • CO_2 emissions are quite low, with CO_2 recovery typically 80–95 percent by adsorption and 90–98 percent by absorption)	• Large process equipment sizes and high costs when the concentration of CO_2 is low (typically <6 percent) • CO_2 capture at low concentrations requires strong chemical solvents and solvent regeneration to separate and capture CO_2 and uses significant amounts of energy • Amine technologies result in a nearly 30 percent drop in net power production and an 11 percent reduction in overall efficiency • Chemical absorption involves solvent degradation and evaporative losses

Oxy-fuel combustion

Despite some attempts at commercialisation of oxy-fuel combustion technology, the separation processes involved (using an energy-intensive unit to remove nitrogen from air to obtain high-purity oxygen) constitute a likely barrier to commercial implementation. While these processes increase the concentration of CO_2 in the flue gas for easier sequestration, their operating costs are high.

CO_2 separation technologies

For each of the CO_2 capture systems, it is necessary to use appropriate CO_2 separation technologies. The choice of technology depends on process conditions, the partial pressure of CO_2, the composition of the gas to be treated, and the relevant industrial sector.

The key purpose of post-combustion capture is to capture and separate CO_2 following removal of other products contained in the flue gas, such as sulphur dioxide and nitrogen oxides. Currently, absorption based on monoethanolamine (MEA) and its derivatives is the most widespread and commercially available post-combustion technique. The adsorption approach is also employed in post-combustion capture, in the form of either temperature-swing or pressure-swing adsorption processes, as well as calcium looping combustion (CLC). It is also possible to use membranes as an appropriate separation technique to reduce capital costs associated with post-combustion technology.

Industrial processes such as those used in cement, iron and steel, pulp and paper, chemicals and natural gas processing account for around 25 percent of all energy-related CO_2 emissions. Capture can be applied in these industries to significantly reduce global emissions. In some cases, CO_2 is a chemical by-product of these processes, rather than the result of burning fossil fuels. For some hard-to-abate industrial processes (such as cement manufacture and blast furnace steelmaking), which presently have limited alternatives to reduce their emissions, CCS is currently the only commercially available technological option to secure deep emissions reductions.[14] Notably, the Intergovernmental Panel on Climate Change identifies CCS as a vital mitigation tool in the cement industry, given that two-thirds of emissions from cement production stem from chemical reactions that occur when heating limestone into lime. In some cases, alternative decarbonisation options may be more efficient and cost-effective, such as scrap steel recycling or using green hydrogen for direct reduction of iron in the steel industry.[15] Further details on iron and steel are given in Chapter 8.

The separation technologies commonly adopted in various industrial settings are set out in the table below.

Table 5.3: Common CO_2 separation technologies, by industry

Industry sector	Separation technology	TRL
Power generation	• Chemical absorption • Chemical absorption—biomass	9 7 & 8
Cement	• Chemical absorption • Calcium looping • Physical adsorption	7 & 8 7 & 8 6
Iron and steel	• Chemical absorption—direct reduced iron • Physical adsorption—smelt reduction • Physical adsorption—direct reduced iron • Chemical absorption—blast furnace + H_2 enrichment	9 7 & 8 6 6
Ammonia production	• Chemical/physical adsorption • Physical adsorption	9 6
Methanol production	• Chemical absorption • Physical adsorption	9 7 & 8
High-value chemicals	• Chemical/physical absorption	7 & 8

The common CO_2 separation technologies are briefly described below:

- **Chemical absorption**: The separation process is based on the reaction of a chemical solvent with CO_2, creating a new intermediate by means of a reversible chemical reaction. Chemical absorption is the most mature CO_2 separation technology and has been used commercially in industrial applications for several decades.
- **Physical absorption**: CO_2 can be physically absorbed in various solvents. As absorption does not involve chemical reactions, the regeneration of the solvent is generally a simple process that involves increasing the temperature, reducing the pressure, or both. It is commercially used to remove acid gases from natural gas and to capture CO_2 from syngas during ammonia, methanol and hydrogen production. Some CO_2 capture methodologies combine physical and chemical solvents.
- **Calcium looping**: This is a relatively new technology for post-combustion CO_2 capture based on the reversible reaction of calcium carbonate into calcium oxide and carbon dioxide. The sorbent (calcium oxide) is regenerated in an oxy-fired calciner, releasing CO_2 that can be compressed and stored or used.
- **Adsorption**: Porous solid adsorbents with large surface areas are used to bind CO_2. After adsorption, CO_2 is removed from the adsorbent layer, usually by pressure reduction or temperature increase.

The table below outlines the advantages and disadvantages of some of the separation technologies[16] applicable to the industry sectors noted above. Other separation technologies are in development, but at an earlier stage (<TRL6).

Table 5.4: Advantages and disadvantages of CO_2 separation technologies

Technology	Advantages	Disadvantages
Chemical absorption	• Simple and suitable for low CO_2 partial pressures • Suitable for retrofitting • High absorption capacities • Product purity >99 percent volume	• Need to pre-clean the exhaust gases • Corrosion of process equipment • High energy demand for regenerating the solvent • Solvent toxicity and loss • Large absorber volume
Physical absorption	• >90 percent CO_2 separation efficiency • Low energy consumption for sorbent regeneration • Regeneration temperature required is lower than for chemical methods • Low corrosivity and toxicity	• Low effectiveness of CO_2 capture • Low selectivity toward CO_2 • Solvents work best at low temperatures • High capital and operating costs • Less economical at a lower partial pressure of CO_2
Calcium looping	• Inexpensive raw materials for sorbents synthesis • Optimal method for retrofitting pulverised coal-fired power plants, sorption-enhanced hydrogen production processes, and BECCS • Minimal reduction in power plant efficiency	• Reduced CO_2 uptake due to sintering of sorbents over many cycles • Additional expenses related to rapid degradation of sorbents • Waste management of sorbents • Need for pure oxygen in some calcium looping processes
Adsorption	• >85 percent CO_2 separation efficiency • Ease of use and maintenance • Low waste generation since adsorbents can be reused • Reversible process (physical adsorption) • Large selection of materials with high CO_2 uptake • Low energy requirement to regenerate adsorbent material • Wide operability range • May use waste biomass or industrial residues as raw materials for adsorbent synthesis	• Low CO_2 selectivity • Lower CO_2 uptake compared to other technologies, such as absorption • Equipment fouling • Scalability • Low resistance to high temperatures • Cost and availability of adsorbents on large scales • Sensitivity to sulphur/nitrogen oxide and moisture • Poor durability of adsorbents

Technology	Advantages	Disadvantages
	• Less toxic and easier to handle compared with liquid absorbents • Applicable to a wide range of capture technologies • CO_2 capture from biogas using membrane or adsorption at TRL9	

Membrane technologies

Membrane separation employs a thin layer of semipermeable barrier material that separates a given gaseous medium when a driving force (e.g., pressure difference, temperature or electric potential) is applied across the membrane. It is a promising next-generation technology for post-combustion CO_2 capture that can significantly reduce energy consumption and chemical footprint relative to mature amine absorption technologies. Despite many efforts, commercially viable membranes have not been widely implemented on a large scale.[17]

Future-oriented strategies for separation technologies

Below are some of the key future strategies for separation technologies that need to be developed to facilitate expedited commercial deployment at scale.

Chemical and physical absorption

- Development of **new solvents** that:
  - have higher absorptive capacities than present solvents
  - require less energy for regeneration
  - are less susceptible to degradation
  - are easier to reclaim and regenerate

- Development of **desorbers utilizing electricity as the energy source:**
  - directly via resistance or inductive heating
  - indirectly via electric steam generation

- Creation of a **coordinated international effort** to develop liquid absorption processes for CO_2 capture. At present, there is substantial fragmentation and duplication of efforts to deal with CO_2 capture by absorption processes. Given its global importance, such an effort should be implemented.

Calcium looping

- Develop sorbent materials that are more resistant to degradation; this will reduce both the frequency of purging part of the sorbent and the disposal of sorbent material, thereby improving the cost-effectiveness of the process.

Adsorbents[18]

- Improved cost-effectiveness of adsorbent production
- Increased functional life of adsorbents
- Effective integration of the contactor (adsorbent beds), solid sorbent technologies (mainly a method of adsorbent regeneration), and adsorbent material in the CO_2 capture phase

- More sophisticated modelling to screen the numerous potential structures of new adsorbents and predict performance under industrial process conditions.

Membranes[19]

- Improve efficiencies at low CO_2 concentrations and high temperatures
- Achieve higher recovery rates with higher purity by membranes, combined with innovative process design
- Develop membrane materials with increased longevity and improved stability, including polymer materials with high resistance to contaminants, such as sulphur and nitrogen oxides in flue gases and high-wetting resistance of polymeric materials in membrane contactors
- Improve process simulations to analyse membrane system design and process feasibility, particularly as functions of CO_2 feed concentration change and key performance parameters, such as energy consumption and operating costs.

Transport

Significant amounts of CO_2 are transported as a dense phase fluid (above the critical pressure but below the critical temperature), since the dense phase offers the most energy-efficient and cost-effective condition. The two most technically mature advanced transport methods are onshore and offshore pipelines and ship transport. CO_2 can also be transported by road and rail tanker. These transport technologies have reached TRL9 and are now used on a commercial scale. Pipeline costs are nominally proportional to distance between the CO_2 source and the storage site and the capacity of the pipeline. There are benefits from economies of scale, which is why the concept of storage hubs is receiving increased attention. Shipping transport costs for CO_2 are less dependent on distance and scale of transport and can be more economical for long distances and smaller volumes. Issues surrounding marine shipping of CO_2 and associated infrastructure have recently been examined.[20] It is likely to become commercially viable in the near future.

In the United States, there is a large-scale network of CO_2 pipelines totalling several thousand kilometres that was established for enhanced oil recovery (EOR); in these cases, the CO_2 is frequently natural or geological. That same pipeline network is available for transport of CO_2 for non-EOR storage.

Storage

The most common method of storing carbon dioxide is underground, by injecting it into an appropriate deep geological environment, usually within a sedimentary basin. This is typically a geological formation or intervals composed of porous and permeable sediments such as sandstones, overlain by impermeable rocks, which act as a seal and prevent the upward leakage of CO_2. The geology needs to be structurally stable and frequently also hosts deep saline aquifers. Depleted oil and gas fields often provide opportunities for geological storage and have the advantage of comprehensive sub-surface data sets that provide a high degree of confidence that the site has suitable reservoir rocks, the CO_2 capacity and injectivity of the site, the likely long-term behaviour of the stored CO_2 and confidence that it will not escape to the atmosphere but will remain safely stored in the subsurface for geological time—essentially forever.

Currently there are several CCS projects in operation in Canada, Norway, the United States, Brazil, Australia and the Middle East, and more are at an advanced stage of planning or under construction elsewhere in Europe and Southeast Asia. However, the majority of current CCS-type operations are small-scale CO_2-based enhanced oil recovery operations (CO_2–EOR). EOR has been a common practice of the oil industry, particularly in the United States, and is seen as analogous to CCS and/or as a “use” of CO_2 (CCUS). However, in reality, much of the CO_2 used in EOR is not anthropogenic and the outcome sought is not permanent storage of CO_2 but more oil production, which in turn results in more CO_2 emissions to the atmosphere. Nonetheless, EOR operations have provided a great deal of CCS-relevant data, and it is possible that EOR operations could be modified to significantly increase and perhaps even maximise the amount of CO_2 stored, but that is not generally done at the present time.

In addition to deep geological storage in sedimentary rock, a further mechanism for CO_2 storage is the geological process of mineral storage, where captured CO_2 is reached with naturally occurring iron (Fe), magnesium (Mg) and calcium (Ca) minerals. This “mineral carbonation” occurs naturally in the weathering of rock over time. Such minerals are very abundant and stable. However, these carbonation reactions are very slow under normal conditions, and to speed them up requires energy to increase temperature and pressure to ideal levels. Some areas of the world, such as parts of India, China and Africa, lack suitable sedimentary basins. For such areas, some igneous rocks may offer a storage option. For example, basalts commonly lack intergranular porosity and permeability, but may have fracture porosity into which CO_2 can be injected. The CO_2 then reacts with alkaline earth metals in basalts containing silicate groups to form stable carbonate minerals within the basaltic sequence. This process has been investigated[21] but is still at a relatively early TRL stage.

Table 5.5 provides a summary of the technological status of various carbon-storage environments.

Table 5.5: Technological status of various carbon-storage environments

Storage method	Status	TRL
Sedimentary formations	• CO_2 rapid injection at a significant rate • Injected CO_2 can be monitored and storage is permanent • The tools required to identify and appraise reservoir capabilities are well-established • Low economic costs	9
CO_2–EOR	• Proven storage locations • Maximises oil recovery • More specific monitoring can ensure that the CO_2 injected is stored permanently	9
CO_2–EGR*	• Proven storage locations • Maximises natural gas and gas condensate recovery • Tight and low-permeability reservoirs	7

Depleted oil and natural gas fields	• Technically mature • Sealed structures • Demonstration projects	7+
Mineral carbonation (e.g. basaltic rocks)	• High–medium storage potential • Storage is safe and durable • Permeability of rocks is difficult to predict • Majority of tools for conventional CCS cannot be applied to monitor CO_2 distribution in in basaltic formations	4 and below

*Enhanced gas recovery

Carbon dioxide removal technologies

Two carbon dioxide removal (CDR) technologies generate negative emissions by combining carbon capture and storage with bioenergy (BECCS and WECCS) or by combining direct air capture (DAC) with storage. These technologies were briefly noted in the introduction, and more details are provided below.

BECCS and WECCS

Bioenergy with carbon capture and storage technology involves not only the generation of energy from biomass (e.g., forestry residues, energy crops or agricultural residues and biodegradable waste products), but also the combined effect of photosynthesis with the subsequent capture of CO_2 and its geological storage. Bioenergy production coupled with carbon capture and storage (CCS) is referred to as BECCS and has reached TRL7 in the industry sector and TRL4 in the energy sector.

Energy derived from combustion of municipal and other waste, coupled with CCS (WECCS), is receiving increased attention, particularly in Europe. BECCS and WECCS can potentially make an important contribution to achieving required CO_2 emissions reductions, whether used individually or as part of a cost-effective unified strategy to achieve negative emissions and a net reduction in atmospheric CO_2 emissions. The magnitude of BECCS' impact varies based on the scale of deployment and the location of biomass cultivation (including emissions associated with earlier land use and indirect change in land use). It is important to consider the net effects of BECCS, since they also contribute to emissions caused by changes in land use and foregone sequestration.

A recent comprehensive review[22] of biomass-based thermochemical conversion technologies integrated with CCS and utilisation, including technology readiness assessments, concluded that combustion and gasification processes are mature and have the potential to be applied within BECCS systems at a commercial scale.

DAC

Direct air capture (DAC) carbon removal technology (TRL5 or 6, Prototype stage) shows promise and will likely be part of a future carbon-removal portfolio. As is the case with other capture technologies, captured CO_2 from DAC can potentially be sold for use in products from concrete aggregate to carbon fibre to synthetic fuels; however, such markets usually do not provide sufficient revenue to offset the cost of capture. The greatest potential climate benefit for DAC comes from combining it with geological sequestration (DACCS), but several critical issues must be addressed before it can be successfully deployed at scale. Some of these include:[23]

- Energy requirements are substantial, and energy sources need to be zero- or very low-carbon to maximise net capture efficiency. Solid sorbent systems are estimated to require around 8 GJ/t of CO_2. Electro-swing adsorption separation technology has the potential to reduce the energy intensity of these processes.
- Significant land area is required for the renewable energy generation that is associated with large-scale deployment of DACCS.
- Water usage associated with direct air capture also depends on the system type and can be significant (1–7 tonnes of water/t of CO_2 captured for a solvent-based system).

A roadmap to 2050[24] to achieve commercial deployment of DAC has been proposed. A review of DAC technologies identified a set of critical priority initiatives that could help overcome the most important impediments to deployment, such as materials, technical and infrastructure-related obstacles to large-scale commercial deployment.

Further, a recent report[25] provides an analysis of the role of CDR (both biological-based and technology-based solutions) in reaching net zero emissions. Issues examined include the market potential for CDR, investment requirements (including levelised cost estimates over time) and market trends. The report also identifies which actions are the most likely to lower barriers to scaling CDR and delineates the potential advantages for first movers in different stakeholder groups.

Summary

As the midpoint of the century approaches, there will be multi-billion-tonne scale demand per year for CCS (whereas current deployment rates are some 50 Mt of CO_2 sequestered per year) and carbon dioxide removal technologies along with deep emissions reductions. However, there will be significant challenges to meet this demand for CCS.[c] The most critical challenges include:

- **Technological**: As has been outlined, numerous technological challenges remain to increase the amount of CO_2 sequestered via CCS. There are significant challenges in moving to higher technology readiness levels (TRL), from research through laboratory and prototype testing to pilot evaluation and then commercial deployment of the technology. CCS technologies are at various stages of development. While many of them need to move higher up the TRL scale, others are at or near commercial deployment, but require further development to achieve widespread commercial use.

- **Cost**: The cost of capturing CO_2 can vary significantly and is a strong function of the CO_2 concentration in the gas stream from which CO_2 is to be removed. In general, the challenge is to reduce the cost of capture and storage as technologies move from the demonstration stage to full commercial deployment. The cost of CCS is often seen as an additional barrier to achieving net zero emissions, unless there are opportunities to offset some of these costs under

[c] Many of the comments made here with respect to CCS also apply to technology-based CDR approaches.

various carbon pricing and incentive schemes. Nonetheless, the use of CCS to decrease industrial emissions will always be significantly less expensive than offsetting industrial emission via DAC, given the low concentration of CO_2 in the atmosphere.

- **Duration**: One of the most pressing needs will be to reduce the current excessive time it takes to identify, approve, develop and commence sequestration operations. While site approval is usually a major factor, the use of depleted oil and gas fields for CO_2 storage offers a cost- and time-effective, low-risk option for deploying CCS at scale.

- **International collaboration**: There is a very large gap between current levels of CCS and the levels required to achieve net zero emissions by 2050. Given the global importance of realising adequate sequestration levels of CCS by mid-century, the equally significant technological and economic challenges and development delays that exist at present, and the current substantial fragmentation and duplication of efforts to deal with most aspects of CCS development and deployment, it is strongly recommended that close national and international collaboration be supported. The IEA Greenhouse Gas R&D programme (IEAGHG) plays a crucial role in facilitating international collaboration in CCS. It brings together academic and government research and development organisations, industry, regulatory and policy bodies, and the financial sector. Furthermore, it would be helpful to develop alignment between international collaboration strategies with specific, operational mechanisms under the Paris Agreement. For example, Article 6.2 of the Agreement promotes bilateral cooperation among the contracting parties, while securing sufficient additional funding from the global carbon credit market.

  An important role for CAETS is to increase awareness among government, industry, and society that the development of climate mitigation technologies such as CCS, BECCS, WECCS, DAC, and DACCS requires a long-term funding commitment from governments if international climate undertakings are to be met. In terms of technical issues, CAETS could have a role in ensuring that governments and regulators understand the importance and desirability of providing durable (namely, permanent) storage when compared with some shorter-term options.

- **Policy environment**: It is essential that long-term, stable policy environments are instituted to help secure the large investments needed for CCS projects, which typically have lifespans of 20 to 40 years.

- **Social licence**: To achieve effective deployment rates for CCS projects, it is essential that project proponents enter into comprehensive engagement with relevant stakeholders, and in particular community stakeholders. A commitment to listen and respond to their concerns and expectations is essential. The achievement of a social licence to operate is fundamental to the success of any proposed CCS project.

- **General:** Delivering a net zero outcome and the lowering of barriers to scaling both CCS and CDR technologies are challenging endeavours. The challenges include: the need for governments and early-stage investors to directly fund technology development; for regulators to expedite the approval process for sequestration projects and to take a measured and realistic approach to risk assessment; to adopt innovative financing arrangements that help catalyse further private investment; to enhance project-level economics that reduce costs and improve future revenue streams; to improve transparency of standards, practices and services; to commit to clear public-sector policy measures and public funding signals; to increase innovation to unlock lower-cost solutions; and to integrate CCS and CDR into cap-and-trade or carbon tax systems.

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6. Chemical industry

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The chemical industry is a vast, complex, integrated, capital- and energy-intensive industry that uses hydrocarbons, minerals and natural products as feedstocks. It is a significant supplier of raw materials to a wide array of other industrial sectors. The total annual production of the chemical industry is estimated to be 960 million tons, with plastic polymers, synthetic fibres and rubber accounting for 420 million tons, N-fertilisers for 290 million tons and other chemicals for 290 million tons.[1,2] A total of 500 million toe/yr[a] of hydrocarbons are used as feedstocks.

On a global scale, the chemical industry consumes 14 percent of total oil demand, amounting to 13 million barrels per day, and 8 percent of natural gas, totalling 300 billion cubic meters per day. A significant proportion, amounting to 50 percent of the total hydrocarbons consumed, is used as raw materials, providing the carbon and hydrogen atoms that are integral to the chemical industry. The industry's current emissions total 1.5 Gt CO_2/yr, accounting for approximately 18 percent of all industry emissions and 5 percent of total energy-related global emissions.[3]

The chemical industry's capacity to rapidly generate novel products is evidenced by its transformation from negligible production levels of plastic polymers in 1950 to a current output of over 400 million tons per year. Given this historical precedent, it is reasonable to conclude that the industry will continue to evolve in the coming decades.

The industry has set ambitious targets to achieve net-zero greenhouse gas emissions from its direct operations (Scope 1) and indirect emissions from purchased power and heat (Scope 2) by the year 2050. To achieve this, the industry is leveraging current technologies, including low-carbon electricity and carbon capture and storage (CCS), which are already available or are in development. Addressing Scope 3 emissions, which are associated with upstream and downstream processes and product disposal at the end of their useful life, is more complex and uncertain, especially when considering broader environmental issues.

Achieving progress on all three scopes requires the implementation of supportive, coherent regulations and incentives, including taxes and subsidies. The role of government policies aimed at replacing hydrocarbons with renewables, using carbon capture and use (CCU) and bio-based feedstocks, is also of significant importance. The

[a] toe/yr indicates tonnes of oil equivalent per year.

use of substantial amounts of green and blue hydrogen is projected to be critical for this transition.[4]

Achieving these objectives requires not only the enhancement of existing process technologies, but also the development of entirely new processes and products that are functionally analogous and, ideally, superior to contemporary ones. A comprehensive transformation within the chemical industry is imperative, requiring technological advancements, substantial financial resources and robust economic, social and political support. It is imperative that these transformations adhere to the tenets of the circular economy, a paradigm that aims to circumvent waste and pollution by ensuring the continuous use and regeneration of natural systems.[5]

Drivers

The working group identified and grouped the following change drivers; however, they did not establish a hierarchy of priorities for these factors.

Non-technical
Demographics (numbers and age distribution) Geopolitics (trade wars, tariffs and duties, changing supply chains) Growth in GDP and free trade Diversity of national and regional conditions Political stability—locally, regionally, nationally and globally Climate change objectives (including Paris Agreement, net zero by ~2050) Sustainability and full life cycle accounting Access to feedstocks, which are dominant cost drivers Markets: size, nature, access, growth Access to and cost of capital Regulations, taxes and incentives Global implementation of carbon emissions accounting, pricing and trading Social acceptance of products and processes Economic impacts (including cost of living) Health and safety Expert workforce Research, development and innovation Equality, diversity and inclusion (EDI) (possible financial impact)
Inputs and feedstocks
Hydrocarbons, inorganics (salts, O_2, H_2, N_2, etc.), biomass Energy: low-carbon electricity, fuels, heat Water Recyclates (mainly plastics/polymers)
Products
Traditional products: industrial chemicals, agricultural chemicals, hydrocarbon polymers, solvents, speciality chemicals, etc. Novel products: battery materials, carbon capture agents, new polymers (e.g., carbon fibres, silicones), H_2, NH_3 (as energy carrier), graphene (large-scale sustainable production of high-quality graphene is near the top of the list in new product developments), etc. [6,7] Feedstocks for bio-based and biodegradable products (including plastics, fibres, adhesives, paints and lubricants)

Technologies
Improved and new separation processes
Improved and new catalysts (including enzymes)
Advanced electrochemical processes, including high-temperature electrolysis and organic synthesis, electro-thermo-catalytic processes
Feedstock substitution
Drop-in chemicals
Digitisation
GenAI: artificial intelligence has a great potential impact on production, product/process research and marketing that could rapidly change the chemical industry[8]
CO_2 utilisation, including artificial photosynthesis

Critical uncertainties

Critical uncertainties are those drivers that are highly uncertain and important to the long-term future of the chemical industry. Two critical uncertainties were selected, leading to four distinct scenarios:

X-axis: Viability of chemical industry products (low acceptance to high acceptance)
Y-axis: Availability of advanced technologies (widely available to restricted availability)

Scenarios

The following four future scenarios result from the two critical uncertainties and reflect the detailed change drivers stated above.

Figure 6.1: Scenarios

Advanced technologies: widely available

1. Struggling chemical industry

- Non-technical drivers only partially met
- Feedstocks, energy and water are variably available and affordable
- Traditional products only variably accepted, available and affordable
- New products developed, but not competitively marketed
- Technologies for better existing and new products only selectively available
- New technologies developed and used
- Only some large and regional companies do well
- Low international competitiveness
- Poor workforce and innovation capabilities

2. Thriving chemical industry

- Non-technical drivers met
- Feedstocks, energy and water are reliably and affordably available
- Traditional products accepted, available and affordable
- New products developed, available and competitively marketed
- Existing technologies improved
- New technologies developed and used
- Thriving, competitive and diverse players (large and small producers)
- Strong workforce and innovation capabilities

Viability of chemical industry products

Low acceptance ***High acceptance***

3. Declining chemical industry

- Non-technical drivers largely unmet
- Variable and unreliable availability and affordability of feedstocks, energy and water
- Products only locally/regionally accepted, available and affordable
- Few new products developed, available and competitive
- Existing technologies improved but advanced technologies only marginally available and used
- Out-migration from chemical industry regions and instabilities
- Education and innovation systems imperiled
- Only a few large producers thrive

4. Imperiled chemical industry

- Non-technical drivers only partly met
- Variable and unreliable availability and affordability of feedstocks, energy and water
- Products only locally/regionally accepted, available and affordable
- New products developed, available and competitive (products that are safe and sustainable by design)
- Existing technologies improved but advanced technologies only marginally available and used
- Good workforce and innovation capabilities for products, but not technologies
- Companies at risk of becoming non-competitive and takeover targets

Advanced technologies: restricted availability

Strategies

The chemical industry's current overall strategy entails a reduction in Scope 1 and 2 greenhouse gas (GHG) emissions, with the objective of achieving net zero emissions by the year 2050. The following measures are currently being implemented:

- the use of low-carbon power and green and blue hydrogen;
- improved energy efficiencies;
- efforts to reuse, recycle and redesign carbon-based polymers and other materials;
- development of biodegradable plastics;
- increased production of synthetic fuels (e.g., H_2, ammonia, dimethylether,[9] propane[10]) and other fuels without carbon;
- development of technologies for carbon capture and use (CCU) and for carbon capture and storage (CCS), including biological capture, to mitigate CO_2 emissions**.**

The following strategies, with a time horizon of 2040 and beyond, address the four scenarios outlined above, as well as other potential futures not described here:

1. **Producing products that meet sustainability, affordability and market criteria.** These objectives can be realised by:

   - identifying and developing new products, including absorbents and adsorbents for carbon capture, as well as biodegradable polymers derived from bio-based or existing hydrocarbon feedstocks. It is imperative to note that biodegradability under standard temperature and moisture conditions is contingent on molecular composition and structure, rather than the provenance of the feedstock.
   - enhancing the recycling ratio of final plastic products, which currently stands at approximately 16 percent for packaging waste. This objective will be pursued by implementing specific measures, including:
     - mandating increased percentages of recycled materials in virgin plastics. This is currently limited by the substandard quality of recycled plastics;
     - reducing the number of types of plastics and additives used in plastic products;
     - increasing the reuse of plastic products, especially bottles and containers;
     - redesigning plastic composite products and packaging to minimise complex multi-laminations and to strive for high performance, full recyclability and biocompatibility[b] through initial design;
     - enhancing recyclability through sustainable designs, including reversible bond adhesives;
     - making major improvements in both mechanical (the prevailing technology currently employed) and chemical recycling methods, while acknowledging that chemical recycling has the greatest potential for sustainability;
     - empowering users of plastic products to select, use, recycle and dispose of these products in a manner that aligns with sustainability objectives;
     - replacing current conventional plastics with biocompatible plastics and plastic composites;
     - reducing material and energy consumption over the full life cycle of plastics;

[b] Biocompatible products are products that are not harmful or toxic to living organisms and tissues.

- minimising or restricting the availability of single-use plastics;
- minimising landfilling and developing novel processes for landfill mining, using incineration of plastics as a last resource (since it enables energy recovery) and developing new methods of plastic recycling.

Over the past two decades, plastics have experienced the most rapid growth in demand. Packaging applications account for approximately 36 percent of the total demand for plastics. The management of plastic waste represents a significant challenge for the chemical industry. Approximately 10 million tons of plastic are estimated to enter the oceans each year, particularly along Asian coastlines, which has raised significant concerns regarding marine ecosystem health and potential food contamination. In response, the European Union, for example, has instituted a series of regulations pertaining to the recycling, treatment and disposal of used plastics.[11,12,13]

2. Producing major energy carriers.

Examples of large-scale energy carriers that are suitable for the global chemical industry are NH_3 and H_2, which are produced using green power or other clean hydrogen sources, such as methane or methanol with CCS, and geologic hydrogen (see the Oil & Gas chapter). According to the International Energy Agency, "by the end of the decade, it is likely to be cheaper to ship hydrogen across long distances in the form of ammonia or liquid organic hydrogen carriers (LOHC)—and then convert it back to H_2 at its destination—rather than transporting it as liquefied hydrogen.[14]

Methane reforming with CCS will be necessary to compensate for the use of alternative hydrogen fuels and for e-fuel production in sectors that are difficult to decarbonise, such as aviation and marine transportation.

3. Producing unconventional inorganics.

The demand for lithium and other special metals, as well as graphitic materials, is projected to increase significantly for use in electric batteries for both mobile and stationary applications. Projections indicate that battery industry sales could reach $250 billion by 2030,[15] with the number of new battery factories expected to reach 300 by that same year. It is imperative to recognise that cell components account for 60 percent of total battery costs, thereby underscoring the need for effective recycling and recovery of rare materials to align with sustainability objectives.

4. Reducing GHG emissions.

The chemical industry must continue to reduce its GHG emissions through:

- increased use of green electricity and heat (including electrification of crackers and chemical processes);
- enhanced use of thermal and electrical energy storage;
- improved and new energy-efficient processes;
- wider use of CCS, developing reservoirs, pipelines and nature-based solutions;
- developing more sustainable H_2-producing systems, with CH_4 pyrolysis being an example.

5. **Developing and using advanced technologies.**

Such technologies include:

- new catalysts and catalytic processes;
- new separation processes, especially for light molecules;
- new electrochemical and electricity-assisted high-temperature thermo-catalytic processes;[16,17]
- digitisation, computer modeling and artificial intelligence to increase operational efficiencies and safety, reduce waste and guide new product development;
- integration of chemical conversion and separation systems.

6. **Investing in innovation and people.**

Achieving progress in the reduction of GHG emissions and developing novel and sustainable products and processes requires investments in innovation and human capital by:

- enhancing collaboration within the chemical industry, with other industries, (particularly the bio, recycling, ICT, materials and clean-fuel industries) and with academia;
- making industrial, research and academic organisations more attractive to students and practicing professionals. Scholarships and bursaries for students and financial support for professional development of practitioners are major inducements for supporting the chemical industry, especially as it manages the energy transition;
- strengthening of regional and international collaboration, with particular emphasis on new biocompatible and bio-based products and greenhouse gas emission-reduction technologies.

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7. Cement industry

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Motivated by the global challenge of equitably providing infrastructure for all people in the most sustainable and economical ways possible, this chapter seeks to identify technological advancements and strategic trajectories for the cement industry to invest in now and in the coming 15 years to ensure low GHG emissions from energy use beyond the year 2040. The primary focus is on energy-related considerations associated with cement production, aligning with evolving societal demands necessitated by the realities of climate change.

Cement, the hydraulically reactive mineral-based binder in concrete and other cement-based products, is both GHG- and energy-intensive to produce. Optimising structural design, including using higher-strength concrete to reduce member sizes and allow for use of complex shapes (enabled, for example, through 3D-printed formwork[1]), can produce significant reductions in concrete volumes and associated cement consumption. Advances in concrete mixture design will also promote cement reductions[2] and can increase the use of recycled materials as replacements for aggregates. To move toward material circularity, adaptation of structures for new uses and reuse of concrete structural elements have been demonstrated. In regions with limited potable water, low-water/low-cement formulations have been proposed, and concrete produced with seawater and treated sewage water are among the many potential innovations[3,4,5] being explored.

Despite constituting only 10–15 percent of the mass (and less than 10 percent of the volume) of portland cement concrete, the cement clinker itself is responsible for almost 95 percent of the material's embodied energy. For this reason, and because the impacts of construction are considered in the Buildings and Smart Cities chapter of this report, this chapter focuses on the composition and selection (including blending) of cements, addressing topics ranging from manufacturing to the implications of cement formulations on long-term concrete performance.

Due to its unique properties (including water resistance, durability, and the ability to transition from a fluid-like to a solid material, which enables consolidation into complex shapes) and the fact that it can be produced economically, largely from locally sourced materials, at a global scale, concrete is the most-used material on the planet. Its annual consumption is second only to water, which is also a component of concrete.

Vital infrastructure components—including those used in energy production and conveyance (e.g., dams, nuclear structures, footings for turbines and power lines), as well as pipes, canals, culverts, transportation structures, buildings and housing—are all composed of concrete. And concrete structures possess excellent resistance to water and temperature changes, a fact that is particularly advantageous as regions experience more frequent fresh and saltwater flooding and extreme temperatures resulting from climate change.

While some recent trends, including mass construction of taller buildings with timber, suggest that some construction will shift away from concrete, it is likely to remain the most-used material in the world because of the performance and economic advantages noted above. Global per capita cement consumption has increased from approximately 1/4 tonne per person per year in 1996 to just over 1/2 tonne per person per year today,[6] and this can be expected to continue with increased urbanisation in developing countries. Historically, cement consumption has increased as countries increase their investments in infrastructure during industrialisation. A 60% increase in infrastructure growth is projected by 2050, supporting an increase of 2.5 billion people living in urban areas over this period.[7,8]

Much of the growth in cement consumption in recent decades has been driven by developments in China and India, with cement production tripling in Asia from 2001–2014 alone. Future growth will be driven by continued population and economic growth, infrastructure development, and increased prosperity, particularly in Asia, Africa, and Latin America. Europe is the only region where cement production has remained relatively constant since the turn of the 21st century.

In some markets, including the U.S. (which has experienced steady growth in cement use since the Great Recession ca. 2008–09), cement imports play an important role in meeting demand. The energy associated with transportation of commodity materials like cement and other components in concrete (e.g., imports of sand to support construction in the Middle East or distribution of supplementary cementitious materials from areas of abundance to regions lacking those resources) should also be considered. Together, these trends demonstrate that global strategies are needed to significantly curb energy consumption associated with cement production and use.

Background: Supply and demand scenarios to 2040 and beyond

Infrastructure development has historically tracked population growth on both local and regional scales, so it is expected that demand for cement and concrete will increase primarily in Asia, Latin America, and Africa in the coming decades as their economies grow. Developed regions, including Europe and North America, can expect flat or incrementally increased demand. It is important to understand the magnitude and distribution of market growth in order to fully appreciate the need for the cement industry to adapt itself to address climate change.

Historically, the cement industry has a culture of continuous innovation. With the global energy crisis of the 1970s, the industry innovated to reduce energy consumption and maximise cement reactivity. For example, the shift from wet to dry process clinker manufacture and other forms of optimisation in cement manufacturing have resulted in GHG emissions reductions from 1,000–1,100 kg/tonne of cement to approximately 750 kg/tonne in modern cement plants. Increases in the amount of tricalcium silicate (C_3S), the most reactive mineral phase in portland cement, led to higher early strengths, accelerating the rate of construction and supporting reductions in clinker content. Materials innovations, including introduction of nanomaterials like silica fume and calcined clays, together with better construction quality, have substantially increased compressive strength, translating into lower concrete consumption due to increased stress capacity and smaller section sizes.

Today, the industry is vibrant with innovation, as demonstrated by the rapidly growing number of start-up companies and increasing median deal size in the building materials sector, with a compound annual growth rate of 17–20% since 2010. Both private and government funding have increased in this sector, aimed primarily at addressing decarbonisation through innovation.[9] In the following sections, recent and anticipated supply and demand trends, extending to 2040 and beyond, are described according to region.

Europe

Cement consumption across Europe has been flat and is expected to decrease slightly in the coming years due to a combination of factors, including population stagnation and a shift toward more sustainable building practices.[10,11]

Overall, Europe is at the forefront of cement industry decarbonisation. The EU has introduced policies to support the industry's transition to net zero, including the Carbon Border Adjustment Mechanism (CBAM) and the EU Emissions Trading System (EU ETS). The free allowances phase-out is set to begin in 2026. And the EU Innovation Fund has awarded funding to support 12 cement projects, primarily related to carbon capture, use and storage (CCUS). Current efforts to diversify energy resources will also benefit decarbonisation in the cement industry, since the focus in this region is on increasing availability of renewable energy sources.

Asia–Pacific Region

Currently, the Asia-Pacific region is the largest producer and consumer of cement, accounting for more than 70% of world production. This region exhibits a diverse range of cement development scenarios due to varying national conditions and levels of development. These differences profoundly affect the cement industry in each country within the region.

China is the world's largest producer of cement. In 2020, cement production was 2.37 billion tons, and the adoption of advanced precalciner kiln technology is widespread. Based on China Building Materials Academy's prediction, demand for cement has gradually declined in recent years and is projected to decrease to about 1.8 billion tons by 2030 and 570 million tons by 2060.[12] The Chinese government's push for stringent energy efficiency targets has facilitated the adoption of low-carbon cement production technologies, such as the promotion of advanced production equipment, intelligent management and operations, and a high percentage of fuel substitution. According to China's specification,[13] the energy consumption limit in 2021 was 3,136 MJ per ton of cement, which is 7% lower than in 2012.

In other Asian countries, however, increases in cement consumption are projected. Currently, India is the second-largest producer and consumer of cement worldwide. Continued annual growth ranging from 4–10% is expected. Providing "housing for all" is a significant current focus in India: More than 13 million new housing units were constructed between 2015 and 2023, with the country relying on reinforced concrete and concrete blocks for much of that construction.

Other major consumers of cement in this region include Indonesia, Vietnam, Thailand, and the Philippines, also driven by robust construction activities and infrastructure projects. Vietnam is also a significant exporter of cement in the region.

If consumption in India and other Asia–Pacific countries proceeds as expected, growth in this region will represent more than 90% of the envisioned decrease in cement production in China over the same period.[14] China and India have set net-zero targets for the cement industry,[15] but policy frameworks in the region remain largely underdeveloped. A lack of comprehensive policies in these key markets significantly impedes efforts to reduce carbon emissions and improve environmental performance.[16]

North America

In North America, increasing use of blended cements and supplementary cementitious materials (SCMs) is already occurring, with energy and GHG emissions savings scaling with the percentage of clinker replacement. For example, ASTM and CSA standards have been changed to allow clinker reduction through blending with uncalcined limestone. The amount of limestone allowed has increased from up to 5% by mass in Canada and the U.S. since 1983 and 2004, respectively, to up to 15% by mass in 2008 and 2012, respectively. Most cement in Canada contains the higher limestone contents (i.e., approaching 15%), and adoption is nearly 100% in large Canadian markets. The shift from ASTM C150 Type I and I/II cements to ASTM C595 Type IL cements was slower, but has increased since 2022 in the U.S., and Type IL cements accounted for about 60% of the market in 2024. Use of alternative sources of SCMs, ranging from reclaimed coal combustion residuals (such as bottom ash and fly ash) to ground glass or natural pozzolans (including calcined clay) is also on the rise.

Increasing availability of new SCM sources (including manufactured or processed sources), advances in cement manufacture, new cement formulations, and new cement feedstock materials are all likely to be important strategies for decarbonisation in this region. The U.S. Department of Energy (DOE) determined that investments of ~$5–20 billion cumulatively by 2030 and ~$60–120 billion cumulatively by 2050 are needed for full decarbonisation of the U.S. cement industry, demonstrating the scale of investment required globally.[17]

Latin America

Latin America's cement industry is characterised by a diverse range of production capacities across countries. Leading South American producers include Brazil, Argentina, and Colombia, each with significant cement manufacturing infrastructures. Mexico is the second-largest producer in the region after Brazil. In 2022, South America had a combined cement production capacity of approximately 180 million tonnes per year, with actual production levels varying based on economic conditions and domestic demand. For example, Brazil’s 93 cement factories have a production capacity of 94Mt/y, but only produced 63.5Mt in 2022, reflecting a gap in capacity utilisation.

Continued growth in Latin American populations is projected, which will require extensive infrastructure investments. Urbanisation trends further amplify the need for efficient and sustainable cement production to support expanding cities. For example, concrete demand in Brazil is projected to rise by 30–80% between 2023 and 2050. In response to global climate challenges, the Brazilian cement industry launched Roadmap Brazil in 2019, a strategic plan aimed at achieving carbon neutrality by 2050.

A key component of this plan is the shift from traditional carbon-based fuels to alternative energy sources. By 2022, the industry had already replaced 30% of its carbon fuel with co-processed materials, exceeding the 2025 interim goal. Through 2030, the Brazilian cement industry plans to invest approximately $700 million to enhance its facilities and processes, including improved handling and use of residues and integration of more sustainable cement production practices.

Colombia has also led in adopting alternative fuels and improving energy efficiency in cement production. Argentina is investing in reducing carbon emissions and exploring new technologies to enhance the sustainability of its cement industry. More broadly, waste biomass like rice husks and coffee grounds have been used extensively as fuel sources for cement manufacture in both Latin America and Southeast Asia.

Africa

The demand for cement in sub-Saharan Africa is expected to increase tremendously over the next few decades, driven by a population increase rate of 2.6%, among other factors.[18] The absence of limestone in most of the West and Central African countries has led to the import of cement and clinker from afar, leading to higher-than-normal GHG emissions in the ground-to-gate system. In future, it is envisioned that quality limestone would be transported from southern regions of Nigeria, which would reduce GHG emissions due to long-distance transportation and stockpiling costs. The higher demand for Nigerian limestone would lead to increased mining and lower costs, which make it more feasible to import.[19]

Educational and professional institutions have a major responsibility to promote more efficient concrete use through the specification of high-strength concretes, updated prescriptive standards, and recognition of the importance of durability.

South Africa implemented its Carbon Tax Act in 2019; consequently, most of their cement companies are aggressively reducing their liability.[20] This is expected to continue in the future, and may inspire more countries in the region to implement similar laws.

Drivers and critical uncertainties

Global demand for cement is expected to increase annually, but changes in composition and production are also forecast. Some drivers for change and critical uncertainties in the path forward are summarised below.

Drivers

Non-technical
Demographics (numbers, age and geographic distribution, predicted growth) Prosperity Diversity of national and regional conditions Political stability Climate change objectives (including Paris Accord, net zero by 2050) Sustainability Access to reserves and resources, geographic availability of raw and constituent materials in regions of growth Markets: size, nature, access Access to capital and new investments Regulations, materials specifications, and building codes Carbon emissions pricing and trading Social acceptance of products and processes Health and safety Expert workforce and training Research, development, and innovation Equality, diversity, and inclusion (EDI) Reuse and recycling
Inputs and feedstocks
Limestone, clay, marl, gypsum, other (e.g., fly ash) Minerals for blended cements (e.g., fly ash, slag, natural pozzolans, uncalcined limestone) Energy: fossil carbons (coals, hydrocarbons), biomaterials, recyclates (including plastics/polymers, wastes) Electricity
Products
Reduced clinker content (i.e., blended cements including portland limestone cements, increased use of SCMs) Alternative clinker chemistries Highly carbonatable cement-based binders Non-hydraulic binders (e.g., geopolymers or alkali-activated binders, magnesium-based binders)

Technologies
Lower-energy and novel production methods (e.g., chemomechanical processing, heat exchange, microwave production, biological processes)
Use of alternative energy sources (e.g., solar, plasma, electricity, biomaterials, waste combustion, ammonia, hydrogen)
CCS/CCUS
Automation, AI, and process simulation for production optimisation and process re-engineering
Multi-objective optimisation, linking more sustainable compositions to performance, including extended service life
Technologies that support construction and performance in more extreme environments

Critical uncertainties

Critical uncertainties are those drivers that are highly uncertain and important to the long-term future of the cement industry. Two critical uncertainties were selected, leading to four distinct scenarios.

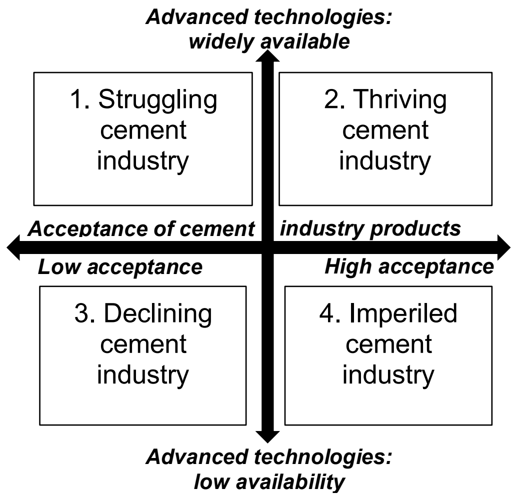
The selected critical uncertainties representing the two axes are:

- X-axis: Cement industry products, ranging from low to high acceptance
- Y-axis: Advanced technologies, ranging from low to high availability

The scenarios can be shown in the form of a two-dimensional figure with four quadrants depicting the scenarios (Figure 8.1). With the current high acceptance and use of cement-based materials, including concrete, combined with the imperative increase in the amount and rate of acceptance of new technologies, the industry today may struggle to meet decarbonisation goals. The solution, as demonstrated in Figure 7.1, is to increase the availability of advanced technologies for cement manufacture and the acceptance of necessary new cement and concrete formulations.

Scenarios

Figure 7.1: Four future scenarios for the cement industry



Scenario 1: Struggling cement industry

- Non-technical drivers partially met
- Variable availability and affordability of feedstocks and energy
- Traditional cements variably accepted, available, and affordable
- New cements developed but not accepted
- Sustainable forms of energy and CCS/CCUS not widely used
- New process technologies developed, but not widely used
- Competing binders a major threat
- Only some large companies do well
- Low competitiveness
- Poor workforce and innovation capabilities
- Structural design codes are outdated and durability-based design is largely absent

Scenario 2: Thriving cement industry

- Non-technical drivers met
- Feedstocks and energy reliably and affordably available
- Traditional cements accepted, available, affordable, and produced with clean energy and CCS/CCUS
- New cements developed, available, addressed in specifications and codes, and competitively marketed
- Existing process technologies improved
- New process technologies developed and used
- Competing binders not a major threat
- Large and small producers thrive and are competitive
- Well-trained and diverse global workforce and innovation capabilities
- Demand is high and continues to increase worldwide

Scenario 3: Declining cement industry

- Non-technical drivers largely unmet
- Highly variable and unreliable availability and affordability of feedstocks and energy
- Conventional cements locally/regionally accepted, available, and affordable
- Novel binders not widely produced, but meet demand
- New processing technologies based on clean energy sources undeveloped
- CCS/CCUS undeployed
- Competing binders a major threat
- Outmigration from cement industry regions; social instabilities
- Education and innovation systems imperiled
- Only a few large companies thrive

Scenario 4: Imperiled cement industry

- Non-technical drivers only partly met
- Highly variable and unreliable availability and affordability of feedstocks and energy
- Conventional cements accepted but not produced with advanced technologies, including CCS/CCUS
- New cements not widely produced or approved in specifications and codes
- Existing technologies improved but advanced technologies only marginally available and used
- Competing binders not a major threat
- Low workforce and innovation capabilities for products, but not for technologies
- Companies at risk of becoming non-competitive and takeover targets

Strategies

The worldwide cement industry sector must become carbon-neutral or even negative as the economy pivots away from fossil fuels.[21] At the same time, the industry must be positioned to robustly address both the rising demand for infrastructure resulting from regional population growth and increasing global affluence and the need for repair and replacement of existing infrastructure due to aging and environmental degradation, which will likely occur at increasing rates. Major new ideas for products and processes are required, along with ingenuity and commitment to developing new ideas, existing technologies, supportive policies and regulations, and large-scale investments.

In that context, and when facing each of the four potential scenarios above, what strategies should the cement sector adopt today? In particular, which strategies might be common to two or more scenarios and therefore more likely to respond to a potential future, even one not explicitly described here?

This working group focused on identifying a few major, industry-specific strategies that are important and innovative, going beyond current general understanding and practices. For example, while it is agreed that the adoption of CCUS and alternative green energy sources are vital to decarbonising this industry, those technologies are broadly needed across most industry sectors and are therefore not detailed here.[a] Key strategies specific to the cement industry that have not gained enough attention in prior endeavours to articulate technology needs are identified below.

Key strategies

Innovations in **raw materials and cement composition** will continue to be important. These may include hydraulic cements with lower calcium carbonate ($CaCO_3$) required in feedstock and other non-clinkered compositions, but the availability and global warming potential (GWP) of the feedstock must match industry needs and goals. Because cements like calcium sulfoaluminate (CSA) and calcium sulfoaluminate belite (CSAB) have been produced in China for almost 20 years without any substantial growth, it is more likely that other innovations in cement composition are needed to secure a foothold in the marketplace. Cements that react with and ultimately store CO_2 during their service life are increasingly of interest, but recent research suggests the potential contribution of this slow process to overall decarbonisation of the industry has been regularly overestimated, at least for conventional cement and concrete formulations.[22] Given that many start-up companies are developing new manufacturing processes and cement compositions, it is difficult at this time to anticipate which, if any, will be widely adopted.

A **shift to blended cements** will be needed in markets that currently rely on bagged clinker-rich materials, such as emerging economies in Latin America, India, and Africa. This is a ripe market for blended cements that can meet project needs. However, switching to cements pre-blended with SCMs in North America and some other developed countries that currently add SCMs at concrete plants will not likely reduce GWP, since the practice of blending is already occurring, just at a different stage. Innovation in the production of SCMs that require calcination can further reduce environmental impact, as described below.

Globally, vast resources of new or underused SCMs, including natural, calcined, and manufactured materials, need to be identified and their production and distribution scaled up. With decreases in coal combustion, the availability of fly ash and other coal combustion residuals conventionally used with cement in concrete is expected to decline. Supplies of granulated blast-furnace slag and silica fume, both also conventionally used SCMs, will not be sufficient to address global needs for use as SCMs or in blended cements to reduce the clinker content of concrete. Aluminate-bearing SCMs (e.g., calcined clays) that will react synergistically with limestone fillers would allow for high clinker replacements without sacrificing early-age performance. With increasing use of limestone-blended cements and increases in the limestone addition rate, approaches to further improve performance of these cements—whether workability, dimensional stability, rate of hardening, or durability—are required.

Changes in the manufacturing process will be important, but these must scale with demand for cement. Therefore, concepts like the production of lime (CaO) from electrochemistry and/or acid-base reactions (rather than calcination) are important because lime produced through these potentially more sustainable processes can be used in cement production (replacing limestone[23,24,25,26]), and co-products such as CO,

[a] For further insights, see National Academies of Sciences, Engineering, and Medicine, *Carbon Utilization Infrastructure, Markets, and Research and Development: A Final Report,* National Academies Press, Washington, D.C., 2024.

formate,[27] methane, ethylene, and ethane can be marketed. And while iron is a minor component in cement manufacture, studies suggest that conventional steel slag or stainless steel slag can catalyse $CaCO_3$ decomposition under CH_4 atmosphere, producing CaO for cement production together with CO and H_2 for subsequent chemical production ($CaCO_3+CH_4 \rightarrow CaO+H_2+CO$, $CaCO_3+H_2 \rightarrow CaO+CO+H_2O$).[28]

Taking this a step further, recent research demonstrates that recycled cement[29] can be substituted for the lime flux used in steel recycling to remove impurities, which normally ends up as a waste product known as slag. By replacing lime with used cement, the end product is a slag cement produced through this combined process[30] of recycling steel and cement.

Strategies that decrease the temperatures required for cement phase synthesis have been identified and need to be scaled up. For example, in a new concept, the temperature required for calcium carbonate decomposition can be reduced by 200℃ under pure hydrogen atmosphere,[31] and the selectivity of CO can be as high as 95.8%. Not only does the co-thermal in-situ reduction of inorganic carbonates inhibit the emission of CO_2, but the CO generated can also be used as raw material for other chemical products.

There is a need for a continued **shift from fossil fuels to electricity, renewable energy, and emerging sources**. The industry already relies widely on combustion of biomass, municipal solid waste, industrial waste, and tires as fuel sources. Future developments can include direct electrical calcination, plasma, oxy-combustion, hydrogen, ammonia, and synthetic fuels (e.g., e-fuels) for both cement manufacture and activation of SCMs, such as clays or shales.

In cement manufacture, total oxy-combustion technology has been developed and facilitates CO_2 capture from the flue gas. The industry has also developed or is developing pilot manufacturing processes relying solely or partially on concentrated solar energy, hydrogen, and ammonia, among other sources. Some approaches, like microwave technologies, have been tried but not successfully scaled up. In the future scenario of large-scale use of green electricity, electrification of the calcination process can be accomplished by using electric heating furnaces, microwave heating furnaces, resistance heating furnaces, electromagnetic induction furnaces, and rotary kiln plasma sealing heads. Plasma generates gas temperatures high enough for clinker calcination. Integrating plasma generation into the rotary kiln burner also minimises the impact on existing process performance.

Another promising energy source for this sector is hydrogen, particularly because of the potential to generate marketable waste streams. By using hydrogen energy combustion technology instead of fossil fuels for preheating materials prior to kiln entry and for calcination, CO_2 emissions can be reduced by about 30%, and the CO_2 concentration of kiln exhaust gas can be increased to 95%, significantly lowering the cost of carbon capture. Further research is needed to better understand the thermal and dynamic characteristics of hydrogen combustion, the jet velocity of hydrogen, and its flame characteristics.

However, because of the existing vast investments in cement plants using large rotary kilns to produce cement, and because such large manufacturing facilities are necessary to meet current and future demand, it is envisioned that any changes in fuel source will, in most cases, be adapted to existing kiln technology. Therefore, marketable co-products (e.g., carbon, methanol) can help to reduce costs. For example, with sufficient energy from wind and photovoltaics, H_2 produced from water electrolysis can be used for cement calcination, and any excess H_2 can react with emitted CO_2 to produce methanol that can be used or sold as a co-product.[32]

Since calcination of SCMs occurs at lower temperatures (i.e., 650–900°C) than portland cement, perhaps even greater early opportunities for innovation exist in the production of natural or alternative sources of pozzolanic materials. With predicted increased demand for SCMs in blended cements and concrete, investments in new production facilities will be required, and these can be designed for efficiency and reliance on green energy sources. Materials with appropriate compositions are well-distributed globally. Relative to cement manufacturing, less attention has been given to increasing efficiencies and innovation while expanding SCM production.

There is a need to **re-establish quantitative measures for long-term performance and service-life prediction**. The industry plays a vital role in providing infrastructure to society. As a result, the industry, owners (often public entities), and society are risk-averse, which is reasonable, since access to energy, clean water, sanitation, and transportation are vital. Increasing climate variability is expected to lead to greater incidence of extreme events and water exposure, causing infrastructure damage with an average cost as high as $845 billion annually, with the effects on infrastructure proportionally greater in less developed countries.[33] Therefore, innovations must be met with reassurance regarding performance. If the concrete can be placed, required strength criteria can generally be met. It will be important, then, to be able to model and predict long-term performance in order to ensure durability. With increasing data available from lab testing, in situ monitoring, etc., machine learning, AI, and data analytics should be leveraged to accelerate model development, considering the multitude of potential new cement chemistries and blended cement formulations. This will be important for both unreinforced and reinforced concrete. Data-supported predictions of long-term performance can support the adoption of new technologies and materials in practice.

Durability should be viewed as a cornerstone of sustainable development. Certainly, extending the service life of concrete reflects a commitment to resource conservation. Quantitative measures of long-term performance are also necessary to support the generation of environmental product declarations (EPDs), which are increasingly used to compare different materials selection and formulation scenarios. These assessment approaches should be standardised to improve their quality and facilitate comparability,[34] since they will likely be used to offer incentives for choosing lower-energy and lower-GWP cement and concrete.

Changes in materials specification, design codes, and construction practices will be needed to support changing cement and concrete formulations. For example, historically, concrete design codes around the world have specified “portland cement”, but a gradual shift toward more inclusive terminology such as "hydraulic cement", which encompasses a broader range of compositions including portland cement, blended cements, and limestone calcined clay cements (LC3), has occurred. European,[35] Canadian,[36] and American[37] standards, for example, now use the broader category of hydraulic cements in their specifications.

Other countries are advancing the use of even broader concrete formulations. Since 2017, China has published a technical specification[38] for the use of calcium sulfoaluminate (CSA) cements in concrete construction, addressing mix design, production, and quality control of CSA cement concrete. Australia has led in the production and commercialisation of geopolymer concrete produced from alkali-activated silicate and aluminosilicate binders. In May 2023, an Australian standard[39] was published that provides requirements and guidance for the design and construction of reinforced geopolymer concrete and alkali-activated binder concrete building structures and members—the first of its kind. Indian standards[40] have also begun to address alkali-activated binders, providing some guidance for the design of alkali-activated slag in a draft specification, for example. Since 2018, Indian standards also reference LC3 cement,[41] outlining its composition and key performance requirements, but without structural design guidance, although a draft design code is in development. In 2014, Cuba was among the first countries to publish specifications addressing LC3 concrete construction,[42] including guidance for structural applications.

Increased awareness of such design guidance, and the resulting experience with construction and operation, is needed to further expand and de-risk the implementation of emerging lower-carbon and alternative cement and concrete compositions.

Given the rate at which these changes are expected to take place, intense **workforce development**, undertaken in a collaborative way that integrates innovators, industry adopters, owners, construction professionals, and educators, will be required. This must be achieved on a global scale, but it is also critical that investments in education and training be made immediately in those regions expected to experience the most rapid development in the coming decades. New generations of diverse and bright talent are needed to drive innovation in the industry.

Finally, **policies that incentivise innovation toward more sustainable concrete infrastructure** are vital. Concrete is a commodity material, and the cement and concrete industry has historically existed with relatively low profit margins. Investments are needed to support innovation, both for existing industry players and to support the emergence and growth of innovators, including start-ups. Further, policies are necessary to incentivise implementation of emerging construction strategies, moving beyond pilot facilities and demonstration projects into routine construction operations.

Implementation: Framing strategies as “grand challenges”

Because of the need for involvement by government and regulatory bodies, industry, researchers and academics, we believe it will be important to frame these as societal “grand challenges”. Policy changes are needed to support an increasingly innovative industry and readily translate these innovations into practice at a rate that meets both increasing infrastructure needs and decarbonisation goals.

At the same time, broad support for data-informed modeling of long-term performance is also vital to de-risk adoption of emerging materials. This will require an integrated and comprehensive strategy as well as buy-in from stakeholders, who range from policy-makers and standard, specification, and code-writing bodies to infrastructure and building owners, contractors and other construction professionals, and the public. Public support is vital because the public is not only served by the infrastructure, but must also pay for it. Material and construction costs will likely increase as a result of the cost of innovation in production and the necessary changes in policy and construction practices to support this.

We believe the idea of grand challenges is a good way of both stating the strategic objectives outlined here for the cement industry and indicating pathways to achieve them. The grand challenges approach has produced significant breakthroughs in a variety of fields, ranging from global health[43] to space travel.[44] Grand challenge approaches are based on clearly defined, ambitious, measurable goals that stimulate broad innovation, engaging diverse participants who can offer new perspectives and expertise to solve longstanding, intractable problems. Participation is incentivised by recognition, including financial rewards that foster competition and drive innovation. Such an approach requires sponsorship.

As described in this chapter, government and private funding (from both industry and external sources) have played a crucial role in nurturing lower-carbon cement technologies. However, to meet the ambitious decarbonisation goals of this critical industry, continued substantial investment is required. This investment will likely come from a combination of government, industry, and philanthropic sources, and will be essential for scaling up these technologies and moving them from pilot facilities to the large-scale production necessary to meet global demand.

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8. Iron and steel industry

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The iron and steel industry, with its current reliance on fossil fuels, is one of the largest global emitters of greenhouse gases, but can also potentially make a substantial contribution to reducing its emissions.[1] The iron and steel industry chapter in the 2022 CAETS report discussed existing, emerging and potential breakthrough technologies for decarbonisation, including the use of hydrogen in shaft furnaces, fluidised-bed reactors, and bio-coke applications in existing processes. While we provide an update on hydrogen utilisation in these breakthrough technologies, this report focuses on low-carbon technologies that are in basic development stages in a laboratory setting or are in the early stages of pilot testing and were not mentioned in the previous report.

The technologies mentioned here are not exhaustive, but have been selected based on the fundamental science involved and their potential impact to lower carbon emissions from the iron and steelmaking process. They include high- and low-temperature electrolysis, methane conversion from CO_2, top-gas recycling for the blast furnace, and plasma utilisation. While large amounts of green H_2 and energy will be essential to realise the breakthrough technologies, these relatively unproven technologies could be less dependent on green H_2 and relatively effective in reducing GHG emissions. Therefore, research collaborations across continents, industries, governments and policies must be effectively combined to address, develop and commercialise these potential technologies.[1]

Drivers

The following are general and specific drivers identified by the working group as likely to impact the iron and steel sector up to and beyond the year 2040, including current and emerging drivers.

General drivers

General drivers	Details
Demographics	• Change in total population impacting demands for iron and steel and derived products • Economic advancement of developing regions, including China and potentially India and Africa
Geopolitics	• Peace versus regional and global conflicts • Wide international collaboration versus isolation and narrow alliances • Access to iron ore and iron and steel technologies • Countries like Korea, which are highly reliant on other countries for energy and raw materials
Geoeconomics	• Open and free trade versus trade blocs and trade barriers • Free versus restricted access to raw materials and essential expertise for iron and steel technologies • Free versus restricted trade in iron and steel products • Movement of capital and access to investment funds: the iron and steel industry is highly capital-intensive and requires large investments with long investment cycles
Prosperity	• Total demand for iron and steel and derived products, where the steel stock in developed economies stabilises around 11 t per inhabitant with an average lifetime of around 45 years • Steel products change from long to more flat as the economy matures and consumption grows
Sustainability	• Full lifecycle accountancy • Meeting net-zero objectives for CO_2 and other greenhouse gases • Striving for circularity, i.e., reduction, reuse and recycling of iron and steel products • Repurposing of iron and steel products
Climate change	• Governments holding iron and steel companies accountable for energy use in iron and steel production and their derived products
Diversity, equity, inclusion	• Proactively addressing gender, social and racial inequities
Asset ownership	• Capital intensity of iron and steel production

General drivers	Details
	● Asset ownership predominantly held by a few major firms or government entities

Current iron and steel-specific drivers

Specific drivers	Details
Electrification	• Availability of renewable energies to be used in iron and steel production: without carbon-free power and/or access to CCS, the industry will be unable to fulfil its commitments • Policies to incentivise investment in low-carbon energy production and provide affordable and plentiful electricity • Location of GHG emissions-free energy sources (including nuclear) close to iron and steel plants • Demand for specialty steels (tungsten, magnet, etc.) - electric motors will greatly increase demand for certain steels and metals
Production	• Cost reduction • Capacity optimisation • Energy utilisation and conservation • Electrification
Education	• Current low-level interest in engineering fields, especially for iron and steel production, is slowing innovation • An industry image not conducive to environmental friendliness and technology innovation seems to deter new engineers

Emerging iron and steel-specific drivers

Specific drivers	Details
Iron ore reducing agents	• Hydrogen issues: production, difficult to transport and store, price[2,3,4] • Ammonia issues: production, easier to transport and store than hydrogen, price[5] • Biomass issues: availability and price, variability in quality, and accurate accounting of its carbon footprint[6] • Electrolysis for iron ore reduction should work, with the technology potentially more efficient than green hydrogen. However, the productivity, availability and developments in blue hydrogen with CCS could make the hydrogen reduction process more economically viable
Slag uses	• Beyond current concrete additives[7,8] • Heavy metals in slags (connection with cement industry)
Recycling	• Separation and recovery of materials from iron and steel products, including base metals (e.g., copper, tin), rare earths (e.g., neodymium from magnets[9]), plastics (e.g., steel–plastic composites); need for good-quality scrap

Specific drivers	Details
New products	• Products such as COASTALUME, a Tedlar polyvinyl fluoride film-coated steel suitable for coastal environments[10] • High Mn[a] TWIP (twinning induced plasticity) steels for cryogenic applications and H_2-related storage and transport

Critical uncertainties

The working group identified two critical uncertainties: drivers that impact the industry sector strongly while also being highly uncertain.

Iron and steel	Two critical uncertainties
x-axis	"Triad" of sustainable, affordable, plentiful materials and energy, ranging from weak to strong
y-axis	Emergence of major new technologies, ranging from restricted to widely available

[a] Manganese

Scenarios

Based on the critical uncertainties noted above, the following four potential future scenarios for the iron and steel sector were developed:

Figure 8.1: Scenarios

Advanced technologies: widely available

1. Struggling iron & steel industries

- Non-technical drivers are partially met
- Raw materials, energy and water are variably available and affordable
- Iron and steel products are unevenly accepted, available and affordable
- Modern production and recycling technologies are only partially available
- Effective competition from nonferrous materials
- CCS and CCUS are not widely deployed
- Only a few large and regional companies are doing well
- Low international competitiveness
- Limited workforce and innovation capacity

2. Thriving iron & steel industries

- Non-technical drivers met
- Feedstocks, energy and water are reliable and affordable
- Traditional products are accepted, available, affordable and competitive
- New products are developed, available and competitively priced
- Existing process technologies are improved
- New process technologies are developed and deployed
- CCS and CCUS are deployed where appropriate
- Many large and small producers are thriving and competitive
- Strong workforce and innovation capabilities

Sustainable, affordable, plentiful materials and energy

Weak ← → ***Strong***

3. Declining iron & steel industries

- Non-technical factors are largely unmet
- Availability and affordability of feedstock, energy and water are variable and unreliable
- Products are locally/regionally accepted, available, affordable and competitive
- Few new products are available
- Improved existing and new process technologies are only marginally used
- CCS and CCUS are not widely used
- Depopulation of iron and steel regions and instabilities
- Education and innovation systems at risk
- Only a few large producers thrive

4. Imperilled iron & steel industries

- Non-technical drivers are partially met
- Raw materials, energy and water are reliably and affordably available
- Existing and new products are locally/regionally accepted, available, affordable and competitive, but not widely produced
- CCS and CCUS are only marginally deployed
- Workforce and innovation capabilities for processes and products are good, but not widely deployed
- Companies at risk of becoming uncompetitive and takeover targets

Advanced technologies: restricted availability

Strategies for lower GHG emissions

This section provides updates on low-GHG-emission technologies currently in commercialisation in major steel-producing countries, with a focus on low-GHG-emission technologies using hydrogen that were previously presented in the CAETS 2022 report. We begin with Japan's COURSE50, followed by China's efforts on HyCROF, Sweden and Finland's HYBRIT, and Korea's developments on the HyREX process.

Japan

The COURSE50 project was initiated in 2008 to develop hydrogen reduction technologies in blast furnaces (see Figure 8.2). A pilot blast furnace (12 m^3, approximately 1/400 scale) has been tested, resulting in a 10 percent reduction of CO_2 in November 2017. In addition, a technology known as the chemical adsorption method is being developed. It uses waste heat to reduce the external energy required for CO_2 capture.

To achieve carbon neutrality by 2050, further R&D beyond COURSE50 is needed. To this end, Nippon Steel, JFE Steel, Kobe Steel and the Japan Research and Development Center for Metals (JRCM) have formed a consortium called GREINS (Green Innovation in Steelmaking). This consortium is developing several technologies in parallel, with support from the Japanese government's Green Innovation (GI) Fund. These include blast furnace hydrogen-reduction technology and direct reduction of iron ore with hydrogen.

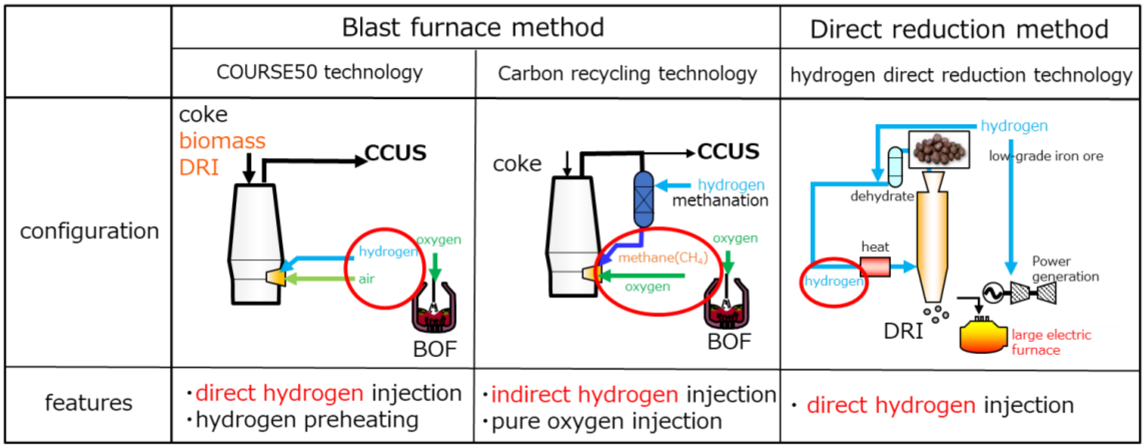
Following the COURSE50 project, the blast furnace hydrogen-reduction technology took a significant leap forward. In the Super COURSE50 project, which introduced external hydrogen into blast furnaces, preheated hydrogen was blown into the test furnace at Kimitsu East Japan Steel Works in 2022. It was confirmed in 2023 that this progress reduces CO_2 emissions by 33 percent, a promising step toward the carbon-neutral goal.

In addition, development is underway for furnace heat compensation technology, furnace operation stabilisation technology using low-grade iron ore, and advanced electric furnace melting technology including impurity removal. These technologies are necessary to produce high-grade steel using direct reduced iron ore with hydrogen.

Carbon dioxide recycling technology is also being developed, where CO_2 is converted to methane and blown into a blast furnace. A 150 m^3 blast furnace demonstration test at JFE Steel's Chiba Works is planned for 2025.

In addition to the above-mentioned industry and government initiatives, separate efforts are underway at universities to develop innovative technologies. For example, the Tokyo Institute of Technology proposed the iACRES (Smart Ironmaking Process based on Active Carbon Recycling Energy System) project, which aims to reduce recovered CO_2 to carbon monoxide (CO) using solid oxide electrolysis cells (SOECs) and reusing recycled carbon as a reducing agent. The project was discussed by a study group set up by the Japan Iron and Steel Institute between 2011 and 2017. This technology is superior in terms of exergy as a carbon cycle, and the development of mounting technologies such as scale-up is currently underway, but practical application issues remain to be resolved.

Figure 8.2: Blast furnace versus direct reduction methods of reducing CO_2



※Depending on the procurement method of hydrogen, there is a possibility that it may be put into the furnace in the form of NH3 instead of H2.

https://www.greins.jp/en/technology/technology02/

https://www.jfe-holdings.co.jp/investor/zaimu/g-data/jfe/2020/2020-environmental-management-vision210525-01.pdf

China

China is committed to becoming carbon-neutral by 2060.[11] With more than half of the world's iron and steel production and consumption,[12] China's iron and steel industry is the second-largest carbon-emitting sector in China, with the integrated steel process (BF-BOF) producing 90 percent of its crude steel.[13] The share of electric arc furnace (EAF) production is limited due to a shortage of high-quality scrap.

Hydrogen-rich and low-carbon blast furnaces (BFs) have been the primary route to achieving low-carbon production on a large scale. The hydrogen-rich carbon recycling oxygen blast furnace (HyCROF) built by Baowu Group separates CO_2 from the furnace top gas and injects recycled byproduct gas (CO) with high reduction potential and green hydrogen into the blast furnace, as depicted in Figure 8.3a. This fully utilises the chemical energy of carbon while replacing fossil-fuel heating with green electricity to further reduce fossil-fuel consumption in the BF. A 400 m^3 HyCROF was tested in 2022 and achieved low carbon operation (coke ratio ~290 kg/tHM and coal ratio ~100 kg/tHM), reducing carbon emissions by more than 20 percent with a maximum utilisation efficiency of 5.0 $t/m^3/d$.[14]

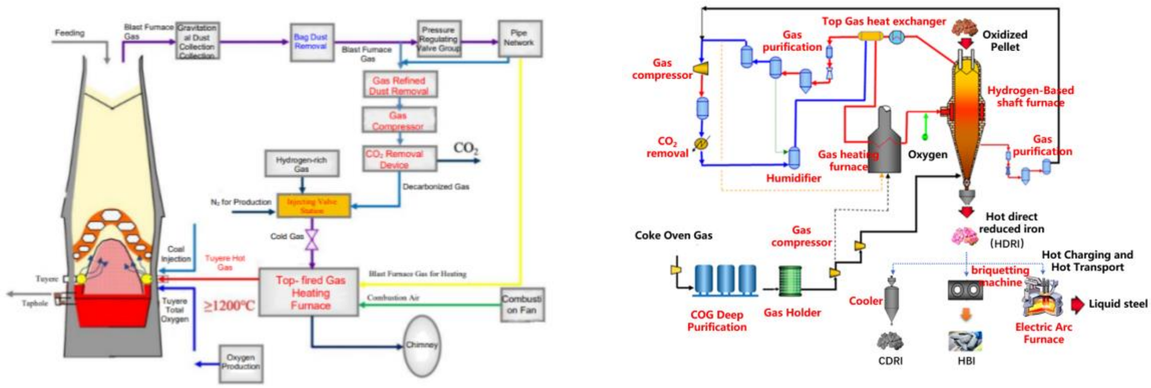
In October 2023, Baowu started a trial operation of a 2,500 m^3 HyCROF commercial demonstration project and achieved good operational results in the first half of 2024. In addition, Jinnan Steel has injected hydrogen-rich gases through the tuyere of the BF with minimal modifications, resulting in reduced fuel consumption and CO_2 generation.

The hydrogen-based direct reduction process is another way to achieve low carbon (see Figure 8.3b),[15] with Zhongjin building and operating the first hydrogen-based direct reduction shaft furnace (like the PERED process) in 2020.[16] Hydrogen derived from coke oven gas (COG) will be used, with an annual production capacity of 0.3 million tons of direct reduced iron (DRI).

In May 2023, the HBIS Group commissioned the world's first zero-reforming COG direct reduction shaft furnace (like the Energiron process) with an annual production capacity of 0.6 million tons of DRI.[17] Compared to the traditional BF-BOF process, the HBIS hydrogen metallurgy demonstration project has the potential to reduce CO_2 emissions by over 70 percent, sulphur dioxide emissions by 30 percent, nitrogen oxide emissions by 70 percent and particulate emissions by over 80 percent annually. In December 2023, Baosteel's 1-Mt hydrogen-based shaft furnace in Zhanjiang marked the first official industrial operation of this type of furnace.[18]

The HIsmelt process was also successfully modified to achieve continuous industrial production at Shandong Molong Petroleum Machinery Co.[19] In addition, Xing-tai Iron & Steel Corp. plans to build a HIsmelt with three 0.55 Mt reduction furnaces, two of which are expected to be completed in 2024.

Figure 8.3: Two ironmaking modifications to reduce CO_2 emission in China



(a) Process flowchart of hydrogen-rich carbon recycling oxygen blast furnace (HyCROF)

(b) Process flowchart of hydrogen metallurgy based on coke oven gas

https://www.researchgate.net/figure/Process-of-oxygen-BF-with-hydrogen-enriched-and-carbon-recycling_fig1_385734298

https://www.sciencedirect.com/topics/engineering/blast-furnace-process; https://www.midrex.com/tech-article/dri-production-using-coke-oven-gas-cog-test-results-of-thermal-reactor-system-trs/

Sweden and Finland

SSAB is the largest steel company in the Nordic countries and the largest CO_2-emitting company in both Sweden and Finland. These two countries have set ambitious climate targets, with Sweden committing to become a fossil-free nation by 2045 and Finland aiming to become carbon-neutral by 2035.

SSAB launched the HYBRIT (hydrogen breakthrough ironmaking technology) initiative with mining company LKAB and energy company Vattenfall in 2016. The project aims to develop a fossil-free value chain from mine to steel, solving the root cause of CO_2 emissions from primary steel production.

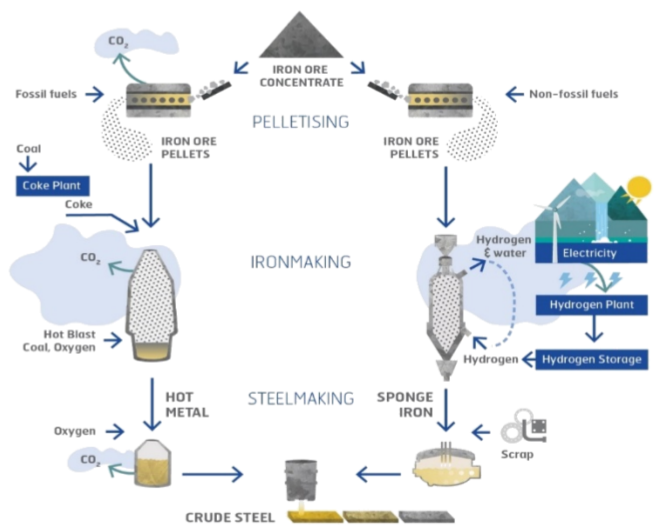
The HYBRIT pilot research program covers the entire value chain, from pellet sintering to hydrogen production using water electrolysis, hydrogen storage, direct reduction of iron ore pellets in the shaft furnace using hydrogen and melting in an EAF (see Figure 8.4). The total budget for the pilot research program is approximately €200 million.

The HYBRIT pilot plant was commissioned in 2020, with successful operation in 2021. Using the HYBRIT direct reduced iron (DRI) from the pilot plant, SSAB produced the first fossil-free steel and delivered it to the Swedish Volvo Group in 2021, where it was used to build the first fossil-free dump truck. SSAB now has more than 50 strategic customer cooperation agreements ranging from mobility to construction, general manufacturing and other customer segments.

Based on customer demand and successful R&D trials, SSAB and LKAB decided to quickly scale up to commercial HYBRIT technology. The first step was to convert SSAB's Oxelösund site into an EAF meltshop, together with a HYBRIT demonstration plant at LKAB's Gällivare site, to be operational by the end of 2026. In 2024, SSAB's board of directors approved an investment of €4.5 billion in a new fossil-free EAF-based mini-mill for premium strip products at the Luleå site, to be commissioned by 2028. SSAB will complete the transformation of its production system in Sweden before 2030, 15 years ahead of its previous target of 2045, with a 10 percent reduction in CO_2 emissions.

Similar to HYBRIT, expanding hydrogen-based reduction platforms to demonstration scale is underway by Stegra, previously known as H2 Green Steel. Construction of the demonstration scale plant at Boden is expected to be completed by 2030, with a 5-MT annual capacity for green steel. The plant will include Europe's largest electrolyser facility, which will produce green hydrogen from water and renewable electricity.

Figure 8.4: Overview of HYBRIT technology process



Schematic overview of the HYBRIT technology from raw materials to processing and energy.
https://www.mdpi.com/2075-4701/10/7/972

Korea

Korea has committed to reducing its CO_2 emissions by 40 percent from 2018 levels by 2030, as outlined in its National Determined Contribution (NDC) at COP26. In line with the NDC, Korean steelmaker POSCO plans to pursue the challenging but proactive path to carbon neutrality while maintaining its current crude steel production capacity. Starting from a baseline average of 78.8 Mt of CO_2 emissions, they plan to achieve a 10 percent reduction by 2030 by optimising production processes through smart technologies and intelligent manufacturing. In parallel, they are developing low-carbon blast-furnace ironmaking technologies to maximise the efficiency of existing facilities. These technologies include increased use of iron-rich raw materials and hydrogen-rich gas in the BF.

In addition, an electric arc furnace for melting scrap is planned to be installed at the Kwangyang steelworks. An innovative technology that maximises the use of scrap in the steelmaking process, known as the top and bottom oxygen blowing converter, is also being developed. Carbon capture, utilisation and storage will also be part of POSCO's low-carbon solution. These technologies are expected to contribute to a 30 percent reduction in CO_2 emissions by 2035 and a 50 percent reduction by 2040.

POSCO also plans to build a HyREX (hydrogen reduction; see Figure 8.5) plant based on fluidised bed reduction technology. The fluidised bed reactor (FBR) uses fine iron ore or sinter feed, which differs from the shaft-type hydrogen reduction technology, which requires high-grade pellets. The abundance of sinter feed iron ore will be advantageous, given the expected shortage of high-quality pellets. The HyREX process involves the hydrogen reduction of fine iron ores with a wide range of particle sizes in multi-stage fluidised bed reactors. Four reactors are installed at different levels and connected by standpipes to facilitate material flow between them. The temperature and residence time in each reactor is optimised to achieve a high degree of reduction to produce direct reduced iron (DRI).

The DRI is then melted in an electrically driven furnace specifically designed for high gangue content. In particular, the physical and chemical properties of fine iron ore have been extensively evaluated with respect to their fluidisation and reduction characteristics, as well as the flowability and adhesion of DRI. To investigate the melting characteristics of DRI, POSCO has constructed a pilot electric smelting furnace (ESF) with a production capacity of 1 t-hot metal/h. Trial operation has begun under various electric power and raw material input conditions. POSCO is currently working on the basic design for a 0.3 MTPA (million ton per annum) HyREX demonstration plant to be built at the Pohang Steel Works.

POSCO operates the world's largest FBRs at its FINEX plants to produce 2.5 MTPA of DRI, with a track record of more than 20 years. The HyREX R&D Partnership, formed by 17 organisations, facilitates the exchange of information about HyREX basic technology development, engineering and construction.

Figure 8.5: The HyREX process

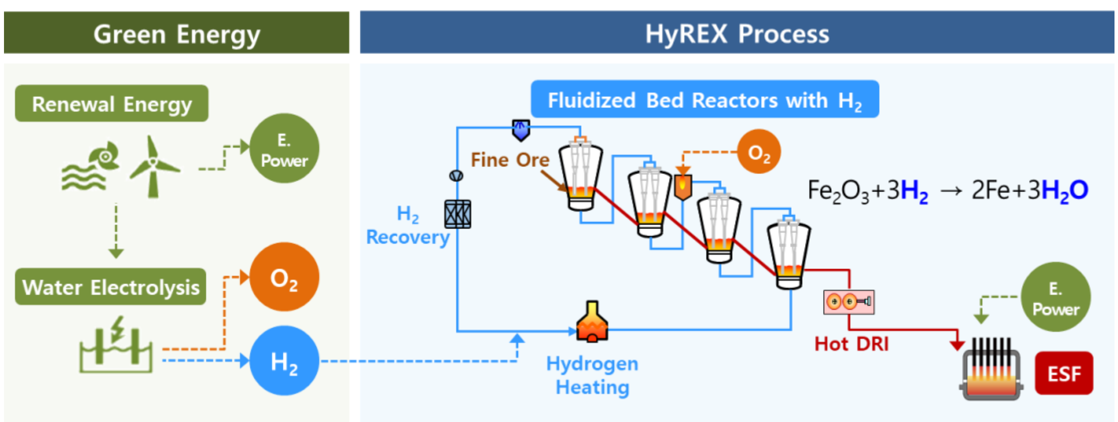


Fig. HyREX process using green energy and the multi-stage FBRs with an ESF.

https://issuu.com/quartzbusinessmedia/docs/sustainable_steel_strategies_summit_september_2022/50
https://pgsjv.com.au/technology/

Potential low-carbon technologies in development

Electrolysis of gases and plasma technology

Technologies for CO_2 electrolysis to CO are rapidly advancing toward commercialisation, especially for BFs with significant CO_2 emissions. Continuous flow electrolysers offer economic feasibility and sufficient reaction rates for such BFs.

The development of plasma reduction technology in metallurgy mainly includes two major categories of applications: one uses the high-temperature properties of plasma as a heat source, including plasma melting, plasma refining and plasma ladle heating; the other uses plasma for direct reduction of oxides, which includes high-temperature and low-temperature plasma reduction.

Electrolysis of iron oxides at low temperatures

In 2002, most European steelmakers, in a consortium of 48 companies and with the support of the EU, undertook a broad investigation of potential technologies to develop ultra-low CO_2 steelmaking (ULCOS) technologies. One of the technologies identified was the reduction of iron ore by direct electrolysis. Initially, two workstreams were launched under the leadership of ArcelorMittal: ULCOWIN low-temperature electrolysis (see Figure 8.6) and ULCOLYSIS high-temperature electrolysis of molten iron ore. At the end of the program, the consortium decided to develop only the cold electrolysis process, as the challenges were considered more manageable compared with high-temperature electrolysis. Cold electrolysis of iron ore was subsequently demonstrated to be feasible on a laboratory scale.

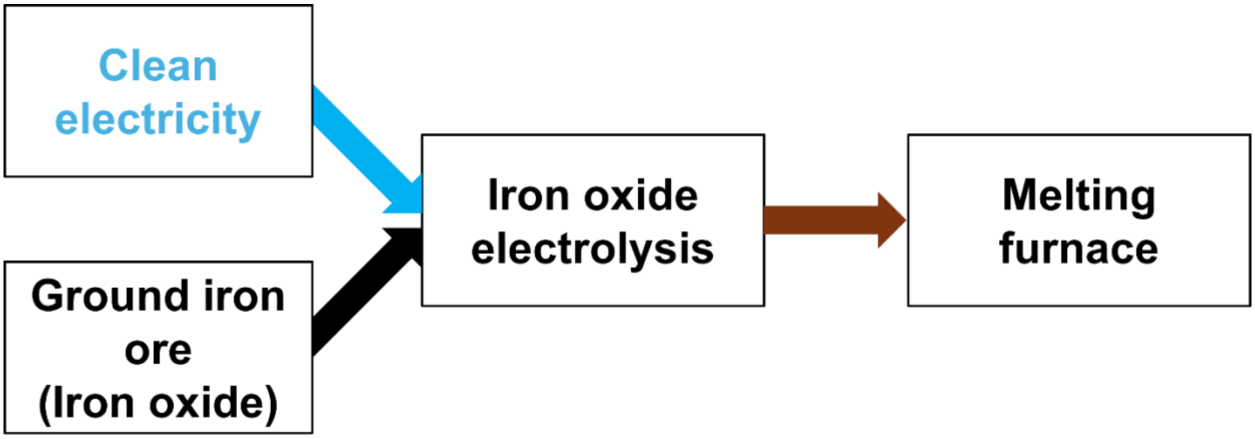
The Electra process is another low-temperature electrolysis process that can utilise several grades of iron ores through acid leaching and electrowinning, producing 99% pure iron and extracting co-products of silica and alumina, thereby reducing waste.

In 2017, on the initiative of ArcelorMittal, the ΣIDERWIN project was launched as part of a program supported by the EU and involving 12 industrial partners. The aim was to develop a radically new steel production process with zero CO_2 emissions. A pilot plant consisting of an industrial-size electrolysis cell (3x1 m) was built to scale up iron production from a few kilos to several hundred kilos. The pilot helped identify the conditions necessary to achieve maximum efficiency by optimising the alkalinity, temperature and flow characteristics of the electrolyte in the cell. The reduction requires oxygen to be evacuated without affecting the current in the cell. The formation of parasitic hydrogen and redox cycling between different iron species must also be avoided.

Tests have also shown that the process can accommodate short shutdowns without significant loss of efficiency, which would allow industrial plants to relieve the grid during peak demand periods. A specific energy requirement of 2.7 MWh/t was achieved under stable conditions. This is significantly less than the current high-temperature, chemical-reducing steelmaking processes. The process uses fine, high-grade iron ore, but also allows iron to be recovered from previously untreatable iron-bearing wastes, such as bauxite residues and slags from copper and ferro-nickel production.

Based on these results, in 2023 ArcelorMittal and John Cockerill joined a consortium with 10 other industrial and scientific partners to bring this technology to maturity. A demonstration plant called VOLTERON will be built. In its first phase, the plant is expected to produce 40 to 80 kt of iron plate per year by 2027. Once the technology has been proven at this scale, the consortium plans to increase the plant's capacity to between 0.3 and 1 Mt per year. After the iron is deposited on a graphite electrode, the deposited iron sheets must be treated in an EAF to melt, treat and cast the steel, further increasing energy consumption. If successful, the use of this technology will depend on the cost and availability of (carbon-free) electricity, for which there is no substitute in this production route.

Figure 8.6: Overview of ULCOWIN technology



Schematic overview of the ULCOWIN technology producing iron connected to EAF.

Electrolysis of iron oxides at high temperatures

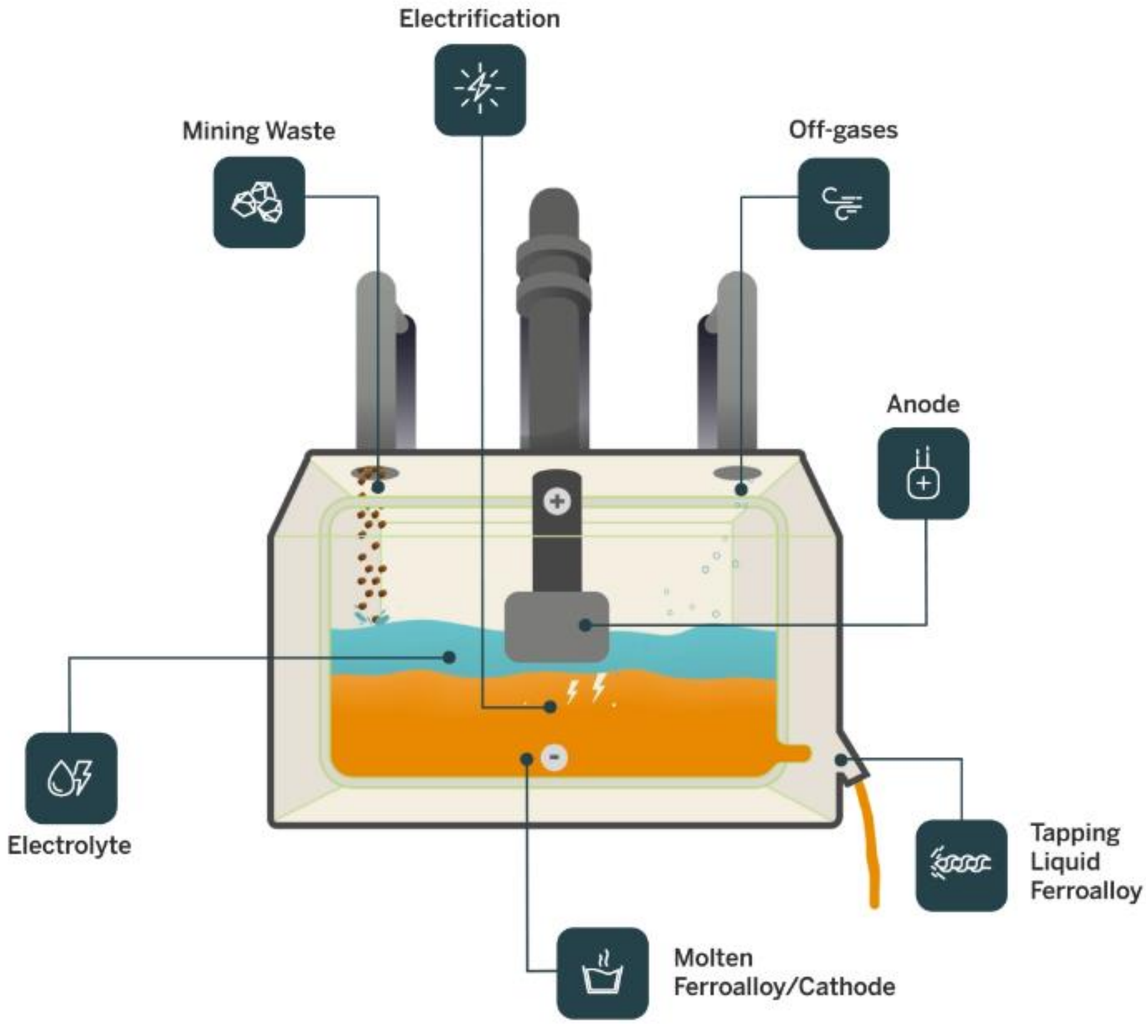
With the support of the U.S. Department of Energy, Boston Metals developed the electrolysis of molten oxides containing iron oxides, known as molten oxide electrolysis (MOE), depicted in Figure 8.7.[20] A chromium-based inert anode is immersed in an electrolyte and an electrical potential is applied to the cell, where the electrons break the bonds of the iron oxide at 1,600 degrees Celsius. A ferro-alloy is produced in a carbon-free process that can generate pure O_2 gas under atmospheric conditions. By controlling the external applied potential, different ferro-alloys can be produced. This technology has been promoted as cost-competitive and sustainable.

The challenges associated with MOE include active control of the viscosity and electrical conductivity of the highly alkaline slag electrolyte due to dynamic changes in composition.[21,22] The electrolyte is based on the SiO_2-CaO-MgO-Al_2O_3 slag system, which maintains lower melting points and viscosity critical to operation. A highly stable inert anode is required, which can be cost-prohibitive depending on the slag system and the ferro-alloys produced.[23,24] Solid oxide membranes have been investigated to improve the stability of the MOE cell, but require continuous operation.

Inert anodes considered in MOE include graphite-based (for use with ferro-alloys and titanium) or iridium-based (for use with iron). Cathodes include titanium or molybdenum plates with lower potentials that can easily accept electrons. At higher temperatures, liquid metals can act as the cathode, accepting electrons and resulting in Joule heating for greater heat compensation.[25]

Compared with the existing carbon-based BF-BOF process, lower energy consumption has been speculated (5.5 MWh coal > 4 MWh electricity from MOE). And compared with the hydrogen-based process, MOE is estimated to have a 35% lower material cost.

Figure 8.7: Overview of MOE technology



Schematic overview of MOE technology producing iron at high temperatures.[20]

Comparison of technologies for lower GHG emissions

A comparison of the various low-GHG emissions technologies is provided in Table 8.1 below. Development of these emerging technologies is still ongoing, and many challenges associated with commercial-scale implementation have yet to be fully resolved. In addition, decarbonisation strategies vary across countries, depending on the availability of raw materials, energy resources and regional infrastructure.

Table 8.1: Comparison of low greenhouse gas emissions technologies

Category	Technology	Region/ developer	Process route	Core principle	CO_2 reduction potential*	Status
BF-based (transitional)	Direct H2 BF injection	Japan (Nippon Steel)	BF (modified)	H_2 injection + CO_2 capture	10% (early phase) up to 30%	Pilot
	H2-enriched Oxygen BF injection	China (Baowu)	BF (modified)	H_2-rich gas injection + recycled purified gas	>20% reduction	Demon-stration
	H2-enriched Air BF injection	Korea (POSCO)	BF (modified)	H_2-rich gas injection	>10% reduction	Industrial
Carbon recycling (transitional)	iACRES	Japan (Tokyo Institute Tech.)	BF + SOEC	$CO_2 \rightarrow CO$ (SOEC)	High potential (with clean electricity)	Lab to early pilot
H_2-DRI (transformational)	HYBRIT	Sweden/ Finland (SSAB, LKAB, Vattenfall)	Shaft furnace + EAF	Green H_2 reduction + EAF	Near-zero (with clean electricity)	Demon-stration
	Stegra (H2 Green Steel)	Sweden	Shaft furnace + EAF	Green H_2 reduction + EAF	Near-zero (with clean electricity)	Under cons-truction
	H_2-DRI (COG-based variants)	China (HBIS, Baowu)	Shaft furnace	H_2-rich gas (COG-derived)	Significant reduction (>70% reported)	Early industrial
	HyREX	Korea (POSCO)	Fluidized bed + ESF	Multi-stage H_2 reduction	High potential (with clean electricity)	Pilot to demon-stration
Electrochemical (disruptive)	Low-temp electrolysis (ULCOWIN/ SIDERWIN/ Electra)	EU / Various Industry	Aqueous electro-lysis	Fe electro-winning from solution	Near-zero (with clean electricity)	Pilot to demon-stration
	High-temp molten oxide electrolysis (MOE)	USA (Boston Metal)	Molten oxide electro-lysis	Direct electro-chemical reduction	Near-zero (with clean electricity)	Pilot
Advanced thermal (disruptive)	Plasma reduction	Various Industry	Plasma reactor	Plasma heat and/or direct reduction	High potential (with clean electricity)	Lab to pilot

Raw materials development for lower carbon emissions in steelmaking

Steel recycling and impurity issues

One of the strategies to achieve carbon neutrality in steel is to promote the recycling of steel scrap. However, the recycling process faces a formidable challenge: impurity contamination. Elements that negatively affect the steel base metal are known as tramp elements (such as copper, nickel and tin). Once these elements are thermodynamically dissolved in the steel base metal, they become extremely difficult to remove. Consequently, the concentration of these impurities becomes increasingly problematic with repeated recycling. These alloys can be inadvertently introduced as impurities during the recovery of steel scrap.

Among these impurities, copper presents a particular challenge during the recycling process. With the increasing electrification of consumer products, including transportation, more copper will be needed. As the concentration of copper increases, it is more likely to cause surface cracking during steelmaking, a phenomenon known as hot shortness cracking. Daehn et al.[26] suggest that if current recycling practices continue, the global concentration of copper in steel materials could exceed acceptable levels (below 0.4%) by 2050. Therefore, the development of effective strategies to mitigate the accumulation of tramp elements is of paramount importance.

Current research efforts are focused on developing technologies to manage copper concentrations, either through additional treatment of copper-rich steel scrap or by using advanced AI techniques for sophisticated sorting and disposal processes. These measures are essential to ensure the continued viability of steel recycling and support the goal of carbon neutrality in the steel industry.

BF- and DR-grade iron ore availability for low-carbon steelmaking

The aforementioned H-DRI production and implementation in the steelmaking process, and particularly in the EAF process, requires higher-grade iron ores compared with the ones used in the BF.[27] While the separation and efficiency of the BF allows the use of BF-grade ores (Fe < 65 wt %), DRI for the EAF and steelmaking process requires lower gangue content to minimise slag volume during processing, and thus DR-grade ores (Fe > 67wt %) are used. Unfortunately, demand for DR-grade iron ores is expected to exceed supply when global EAF steelmaking routes are estimated to exceed 40% of total steel production in 2035. Therefore, additional mining operations to produce DR-grade iron ore or upgrading facilities from BF-grade iron ore to DR-grade iron ore may be required.[28]

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9. Buildings and smart cities

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Climate action in cities is essential for achieving ambitious net-zero emissions goals. Cities currently account for more than 50 percent of the global population (the United Nations' latest figure is 55 percent), 80 percent of global GDP, two-thirds of global energy consumption and more than 70 percent of annual global carbon emissions. These factors are expected to grow significantly in the coming decades: The UN anticipates that by 2050, more than 68 percent of the world's population will live in cities, resulting in massive growth in demand for urban energy infrastructure.[1]

This chapter extends the 2022 CAETS report *Towards Low-GHG Emissions from Energy Use in Selected Sectors*[2] by addressing the following specific focal question:

> *What actions need to be taken now, and in the near future, so that sufficient technologies are available and realistically deployable to ensure low-GHG emissions from energy use in the buildings and smart cities sector beyond the year 2040?*

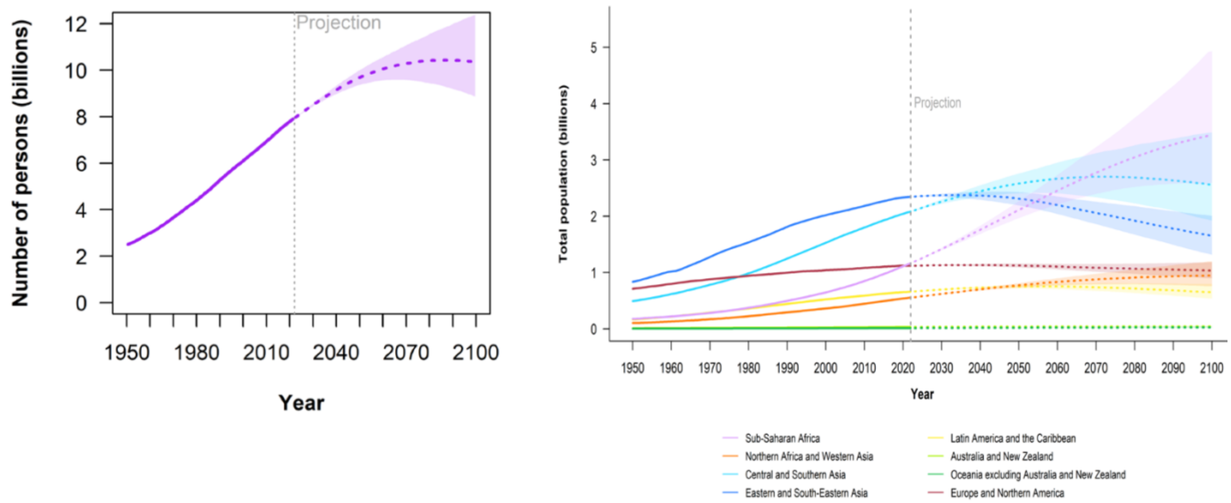
Before responding to the focal question, using the foresight methodology described in the Introduction, it is important to set the scene by providing some pertinent background information and definitions.

Setting the scene

World population

The United Nations estimates (see Figure 9.1) that the world's population is projected to grow from 7.7 billion in 2019 to 8.5 billion in 2030 (a 10 percent increase), 9.7 billion in 2050 (26 percent) and 10.9 billion in 2100 (42 percent).

Figure 9.1: Global population size



(a) (b)

(a) Global population size and medium scenario, 2022–2100 and (b) population by SDG region: estimates, 1950–2022, and medium scenario, 2022–2100. https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022_summary_of_results.pdf

Urban population growth

The urban population of the world has grown rapidly, from 751 million in 1950 to 4.2 billion in 2018. Today, the most urbanised regions include North America (82 percent of the population living in urban areas in 2018), Latin America and the Caribbean (81 percent), Europe (74 percent) and Oceania (68 percent). In contrast, Africa remains mostly rural, with just 43 percent of its population living in urban areas. Asia, despite its relatively lower level of urbanization, is home to 54 percent of the world's urban population, followed by Europe and Africa with 13 percent each.

Migration from rural to urban regions will continue throughout the 21st century. As mentioned above, the United Nations expects that 68 percent of the world's population will live in urban areas by 2050, compared with 55 percent today.[3] They project that urbanisation (the shift in residence from rural to urban areas) combined with overall world population growth could add another 2.5 billion people to urban areas by 2050, with close to 90 percent of this increase expected to take place in Asia and Africa.

These future urban population increases are expected to be concentrated in a small number of countries. Together, India, China and Nigeria will account for 35 percent of projected urban population growth between 2018 and 2050. By 2050, it is estimated that India will have added 416 million urban dwellers, China 255 million, and Nigeria 189 million.

Definitions of urban areas/cities

Definitions of urban areas and cities differ depending on the country, region and reporting organisation. However, there are some common thresholds used to classify an area as urban:

- **Degree of urbanisation (United Nations)**[4,5]

  Three major classes of urbanisation have been adopted by the United Nations: cities, towns and semi-dense areas, and rural areas. Urban areas are defined as cities plus towns and semi-dense areas, with users encouraged to use all three classes because towns and semi-dense areas differ significantly from both cities and rural areas. The UN recommends further subdivision by splitting towns and semi-dense areas into towns and suburban or peri-urban areas and splitting rural areas into villages, dispersed rural areas and mostly uninhabited areas.

  The following definitions apply:
  - **Cities** have a population of at least 50,000 inhabitants in contiguous dense grid cells (more than 1,500 inhabitants per square kilometre).
  - **Towns and semi-dense areas** have populations of at least 5,000 inhabitants in contiguous grid cells (at least 300 inhabitants per square kilometre).
  - **Rural areas** consist mostly of low-density grid cells (fewer than 300 inhabitants per square kilometre).

- **Urban population by city size (OECD)**[6]

  Urban population by city size is determined by population density and commuting patterns; this is thought to better reflect the economic function of cities, in addition to their administrative boundaries.

  Urban areas in OECD countries are classified as **large metropolitan areas** if they have a population of 1.5 million or more; **metropolitan areas** if their population is between 500,000 and 1.5 million; **medium-size urban areas** if their population is between 200,000 and 500,000; and **small urban areas** if their population is between 50,000 and 200,000.

Urban settlements with fewer than one million residents presently predominate, with more than two billion people worldwide living in settlements with fewer than 500,000 inhabitants. This trend is expected to continue even though the total urban population is expected to grow substantially.[7]

Smart cities

While there is presently no universally accepted definition of a smart city, it is generally accepted that smart cities use information and communication technology (ICT) to increase operational efficiency, share information with the public, provide better government service and improve citizen welfare. Alternate definitions include:

- An urban area where technology and data collection help improve quality of life and the sustainability and efficiency of city operations. Smart city technologies used by local governments include information and communication technologies (ICT) and the Internet of Things (IoT).[8]

- A technologically modern urban area that uses electronic methods and sensors to collect specific data. Information gained from that data is used to efficiently manage assets, resources and services; in return, that data is used to improve operations across the city.[9,10]

The main goal of a smart city is to use smart technologies and data analysis to optimise city functions and promote economic prosperity while also improving the health and quality of life of citizens. The value lies in how ICT is used, rather than simply how much ICT is available.

A smart city includes the following set of characteristics:

- technology-based infrastructure
- environmental initiatives
- effective and highly functional public transportation
- confident and progressive city plans
- people able to live and work within the city, using its resources

The success of a smart city relies on the relationship between the public and private sectors, because much of the work to create and maintain a data-driven environment falls outside the local government's remit. For example, smart surveillance cameras typically need professional support and technology from several companies.

In addition to technologies, smart cities also need data analysts who can assess the information provided by the city's systems, so problems can be addressed and improvements made.

Smart city technologies

Smart cities use a variety of software, user interfaces and communication networks alongside the Internet of Things (IoT) to deliver connected solutions for the public. Of these, the IoT is the most important. The IoT is a network of connected devices that communicate and exchange data. These can include everything from vehicles to home appliances and on-street sensors. Data collected from these devices is stored in the cloud or on servers; it allows for improvements to both public and private sector efficiencies and delivers economic and other benefits to citizens.

Many IoT devices use edge computing, which ensures that only the most relevant and important data is delivered over the communication network. In addition, a security system is implemented to protect, monitor and control transmission of data from the smart city network and prevent unauthorised access to the city's data platform.

Smart city features

Smart city technologies improve the efficiency and reliability of all functions carried out in cities, including energy use, manufacturing, provision of services, urban farming and more.

Combining automation, machine learning and the IoT allows adoption of smart city technologies for a variety of applications. For example, smart parking can help drivers find parking spaces and enable digital payment.

Another example is smart traffic management: monitoring traffic flows and optimising traffic lights to reduce congestion. Ride-sharing services can also be managed by smart city infrastructure.

Other features might include energy conservation and environmental efficiencies, such as streetlights that dim when roads are empty. Such smart grid technologies can improve everything from operations to maintenance, planning and power supplies.

Smart city initiatives can also be used to combat climate change and air pollution and improve waste management and sanitation via internet-enabled rubbish collection and fleet management systems.

Beyond services, smart cities can enable safety measures, such as monitoring areas of high crime or using sensors to provide early warning for incidents like floods, landslides, hurricanes or droughts.

Post-2040, the impacts of climate change will continue and likely intensify. All cities, including smart cities, must be resilient to the consequences. Water is a particularly important issue: too much water leads to heightened flood risk, while too little water puts pressure on drinking water resources. Nature-based solutions must play an important part in the environmental sustainability of cities and their relationship with the natural environment. At the same time, buildings and other infrastructure need to be made more resilient, particularly to extreme weather events and other disasters such as fires and earthquakes.

Smart cities must benefit everyone. Initiatives and projects should be designed and deployed in a manner that addresses inequalities and inequities in the community with the overarching goal of inclusivity. Technology is the bedrock of the smart city concept, but for citizens to be engaged and take ownership, there must be proper training and orientation. Smart cities thrive with smart citizens. A major component of the planning effort should focus on social networks, community engagement, citizen orientation, and training on various media.

A brief history of smart cities

In the 1960s and 1970s, the U.S. Community Analysis Bureau began using databases, aerial photography and cluster analysis to collect data, allocate resources and issue reports in order to direct services, mitigate disasters and reduce poverty. This led to the first generation of smart cities, created by technology providers who understood the implications of technology on daily life.

The second generation of smart cities examined how smart technologies and other innovations could create integrated municipal solutions.

The third generation of smart cities removed control from technology providers and city leaders, instead creating a system that involved the public and enabled social inclusion and community engagement. This third-generation model was adopted by Vienna, which created a partnership with the local Wien Energy company that allowed citizens to invest in local solar plants and worked with the public to resolve gender equality and affordable housing issues. Adoption has continued elsewhere, including in Vancouver, where 30,000 citizens co-created the Vancouver Greenest City 2020 Action Plan.

Smart City Index

The essence of smart cities is reflected in the annual Smart City Index put out by the IMD[a] World Competitive Center. It provides "balanced focus on economic and technological aspects of smart cities on the one hand, and humane dimensions of smart cities (quality of life, environment and inclusiveness) on the other."[11] The 20 cities with the highest 2024 rankings are:

1	Zurich	11	Stockholm
2	Oslo	12	Dubai
3	Canberra	13	Beijing
4	Geneva	14	Hamburg
5	Singapore	15	Prague
6	Copenhagen	16	Taipei City
7	Lausanne	17	Seoul
8	London	18	Amsterdam
9	Helsinki	19	Shanghai
10	Abu Dhabi	20	Hong Kong

Summary

The smart city approach underscores the importance of collaboration among diverse stakeholders, including government, business and citizens, to co-create innovative solutions and address intricate urban challenges. By embracing this concept, cities aim to not only upgrade their infrastructure and service provision, but also to nurture social inclusion, technological adoption and economic advancement. Leveraging digital technologies enhances residents' quality of life, promotes sustainability and stimulates economic growth by fostering the emergence of new industries and job opportunities. The smart city concept includes smart and engaged citizens.

Smart buildings

Smart cities incorporate smart buildings that have systems for real-time energy and space management, optimised interaction with smart electric grids, structural health monitoring and feedback to determine when repairs are necessary. Citizens can access these systems to notify officials of problems, while sensors automatically monitor for infrastructure problems, such as leaks in water pipes, and provide alerts. Smart buildings should have levels of resiliency commensurate with local risks, such as earthquakes, periods of drought, heat waves, blackouts and floods. They also include rainwater storage, thermal storage and battery storage for electricity generated from photovoltaic panels.

[a] International Institute for Management Development, https://www.imd.org/.

Cities are home to a diverse range of buildings, each serving different purposes. New building types emerge as urban landscapes evolve. Some common types of buildings in urban areas are:

Residential buildings:

- Single-family detached houses: standalone homes for one family
- Townhouses: attached homes with shared walls
- Apartments/condos: multi-storey buildings with individual dwelling units
- Duplexes, triplexes and quadplexes: multi-family homes
- Retirement homes and nursing homes for seniors

Commercial buildings:

- Office buildings
  - Low-rise: less than 7 stories
  - Mid-rise: 7–25 stories
  - High-rise: over 25 stories, including skyscrapers
- Retail buildings
  - Shops/boutiques/services: single-business buildings
  - Big box stores: large retailers like Walmart or Home Depot
  - Malls: house multiple businesses and services

Infrastructural buildings

- Metro stations: underground transport hubs
- Lighthouses: coastal navigation aids

Public buildings

- Museums, libraries and civic cultural institutions
- Educational institutions
- Palaces, official residences and presidential palaces
- Churches and other religious structures

Industrial buildings:

- Manufacturing plants: factories for production
- Warehouses/distribution centres: storage and logistics
- Flex space: adaptable spaces for various uses

Data centres

Around 80 percent of the buildings that will exist in 2050 are already built (50 percent in Canada). This fact highlights the importance of retrofitting existing buildings to combat climate change by reducing their energy consumption and greenhouse gas emissions but also improving energy efficiency for inclusivity. It emphasizes the need for sustainable construction and maintenance practices in urban infrastructure to meet global warming targets.[12]

Strategies that can be applied include:

- upgrade HVAC systems
- seal and insulate
- address drafty windows and doors
- switch to LED lighting
- install energy-saving appliances
- upgrade electrical systems
- install solar panels
- upgrade water systems
- switch to less-emitting energy sources and develop economical energy storage capacities (PV panels, batteries, ATES, BTES)
- install HEMS and BEMS by connecting the relevant electric equipment and appliances and enhancing thermal inertia
- optimise recycling and reuse

- choose materials and methods to reduce the overall carbon footprint, including consideration of the thermal insulating properties of building materials (concrete, wood, etc.)

These strategies contribute to environmental conservation and can potentially reduce operational costs. It is important to consider the specific context and construction of each building to choose the most appropriate measures.

Drivers

The following current and emerging drivers were identified for the buildings and smart cities sector:

Driver	Details
Energy supply	Electricity and thermal energy supply: • reliability/resiliency (including minimising and coping with blackouts) • affordability
Policies and regulations	• energy efficiency of buildings • building codes, standards and regulations • financial incentives
Electrification	• electrification of personal, industrial and public transportation • thermal energy replacement for domestic and industrial uses, e.g., space heating, cooking, hot water • heat pumps, in particular geothermal heat pumps • energy control with ICT
District thermal energy	District heating[13,14] using: • dedicated, centrally controlled generated energy • low-grade, waste thermal energy from industry
Communication	• public engagement • availability of energy information • energy literacy
Distributed energy generation[15]	• electricity generated by photovoltaics on building roofs[16,17] • electricity generated by photovoltaics on urban infrastructure, e.g., roads,[18,19] parking lots and sidewalks
Energy storage	• large-scale, short- and long-term electrical and thermal energy storage to compensate for variable renewable energy supply and demand[20] • localised and distributed storage[21]
District cooling	• supplement to district heating, reflecting needs driven by ambient temperature rise during summer periods
Smart grid	• ICT and AI for design and predictive operation of buildings, transportation and urban infrastructure
Building materials	Improved and new materials: • renewable structural materials, e.g., cross-laminated timber[22,23] (see the Cement chapter)

Driver	Details
	• use of decarbonised/low-carbon cement compositions • thermal insulating materials for wall units • windows, including glasses and coatings responsive to variable insolation[24,25] • reduce environmental impact of cement and concrete
Construction	• modular construction of buildings and transportation infrastructure to minimise cost, time and disruption • trenchless placement of infrastructure[26] • minimise use of water • implement building "life logs" to facilitate maintenance and reduce costs

Critical uncertainties

Critical uncertainties are those drivers (or forces and factors) that are, for a given subject area (in this case, buildings and smart cities) both important to its future and highly uncertain. If just two critical uncertainties are selected and shown as two perpendicular axes, four quadrants result, each representing a distinct scenario.

The following two critical uncertainties were selected:

X-axis: Collaboration among diverse stakeholders, including government, business and citizens, to co-create innovative solutions and address intricate urban challenges—strong to weak
Y-axis: Emergence and adoption of major new smart technologies for buildings and urban infrastructure, ranging from none to numerous—strong to weak

These gave rise to the four scenarios shown in the figure on the next page.

Scenarios

Figure 9.2: Scenarios

Strong collaboration among diverse stakeholders, including government, business and citizens, to co-create innovative solutions and address intricate urban challenges

1. **Struggling cities:** 4 strategies
   - 1.1 Good, resilient water and energy supply systems are available but lack wide implementation
   - 1.2 Cities are not widely adapted to climate change-driven extreme weather impacts (storms, floods and temperature excesses)
   - 1.3 Public and private building stock is not continuously modernised
   - 1.4 Public and private sector decision-makers and citizens do not have wide support

2. **Thriving cities:** 4 strategies
   - 2.1 Good, resilient water and energy supply systems are in place
   - 2.2 Cities are well-adapted to climate change-driven extreme weather impacts (storms, floods and temperature excesses)
   - 2.3 Public and private building stock is continuously modernised
   - 2.4 Public and private sector decision-makers and citizens are smart and engaged

Adoption and implementation of new smart technologies

Low acceptance ← → ***High acceptance***

3. **Declining cities:** 4 strategies
   - 3.1 Good, resilient water and energy supply systems are largely unavailable
   - 3.2 Cities do not accept the need to adapt to climate change-driven extreme weather impacts (storms, floods and temperature excesses) and adaptations are not deployed
   - 3.3 Public and private building stock is becoming outdated
   - 3.4 Public and private sector decision-makers and citizens lack expertise and judgement

4. **Cities at risk:** 4 strategies
   - 4.1 Good, resilient water and energy supply systems are unavailable
   - 4.2 Cities accept the need to adapt to climate change-driven extreme weather impacts (storms, floods and temperature excesses) but cannot deploy adaptations at sufficient scale
   - 4.3 Public and private building stock not modernised at scale
   - 4.4 Public and private sector decision-makers and citizens are smart and engaged but unable to act

Weak collaboration among diverse stakeholders, including government, business and citizens, to co-create innovative solutions and address intricate urban challenges

Strategies

The following four strategies are proposed:

1. Creation of resilient water and energy systems
2. Adaptation to climate change-driven extreme weather impacts
3. Modernisation of public and private building stock
4. Promotion of smart and engaged public and private decision-makers and citizens

To achieve smart cities, the goals are:

1. Affordable and resilient water and energy supplies
2. Adaption to climate change-driven extreme weather impacts (storms, floods and temperature excesses)
3. Modernised building stock
4. Good expertise and judgement by decision-makers with strong and engaged collaboration among diverse stakeholders

The following strategies are proposed:

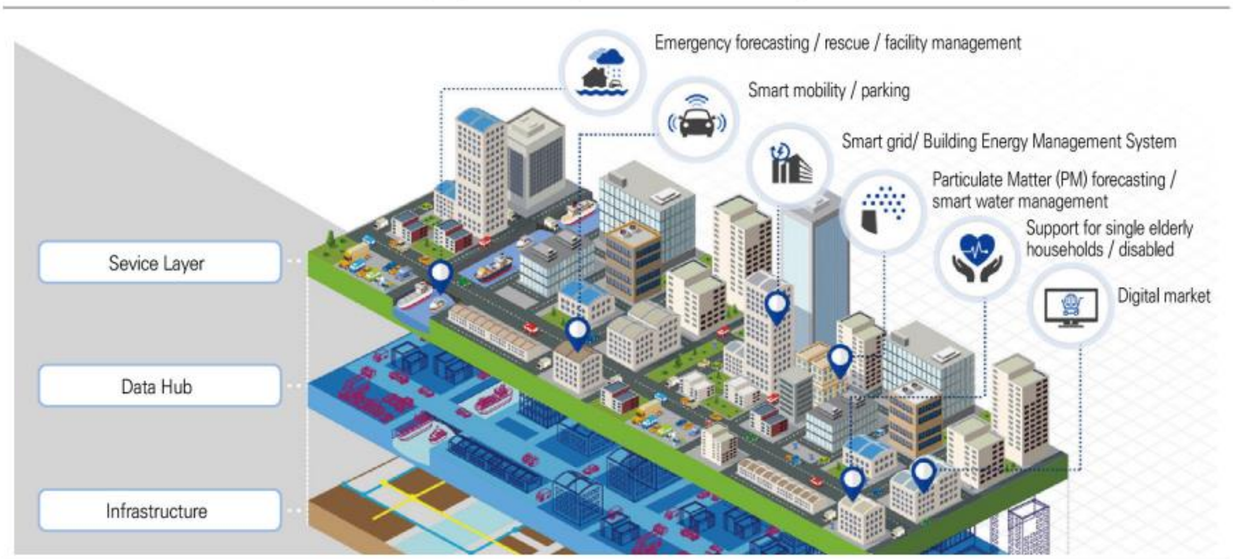
1.	**Ensure buildings and smart cities have available sustainable, affordable and plentiful energy by:** • generating, purchasing and/or storing renewable energy from solar, wind, biomass and other sources with low GHGs • investing in, deploying and maintaining such energy sources • creating incentives to adopt secure energy sources • employing practical learnings, energy audits and AI in the design and operations of buildings and city infrastructure • maximising awareness of energy use through real-time metering, displays and communications • **Ensure smart cities have available and sustainable water and wastewater services by:** • creating efficient and sustainable drinking water storage, treatment and distribution systems • effectively treating wastewater to reduce environmental impact • building sustainable urban drainage systems to address extreme rainfall events
2.	**Ensure cities adapt to climate change-driven extreme weather events by:** • carrying out a full risk assessment of vulnerability to extreme weather events (storms, floods, droughts) • upgrading existing infrastructure • identifying locations of vulnerability and ensuring emergency plans are in place in the design and operations of buildings and city infrastructure • developing resilience at all levels, taking care of the coupling of the different infrastructures
3.	**Modernise public and private building stock by:** • offering incentives, including financial support • ensuring the availability of trained personnel, materials and general support services

4.	**Ensure active citizen engagement by:** • enabling expertise and good judgement in decision-makers and support personnel • proactively developing and sharing communication materials • creating practical learning opportunities through virtual and on-site experiences • creating a wider understanding of the Jevons paradox in the context of energy uses for buildings and smart cities[27] • ensuring strong and engaged collaboration among diverse stakeholders

To support these strategies, the following case study from South Korea is of interest.

South Korea

South Korea has been promoting smart cities as a key greenhouse-gas reduction strategy in the building sector since presenting its 2050 carbon neutrality goal[28] to the United Nations Framework Convention on Climate Change at the end of 2020. According to that strategy, cities with closely connected networks of big data and advanced hydrogen technologies, ICT and transportation systems could provide numerous opportunities to achieve carbon neutrality in the building sector. Future smart cities tightly linked to advanced ICT are expected to offer real-time information about where surplus energy is being produced, so that it can be used where it is most needed. Hydrogen technology is also an option to be considered when seeking to achieve carbon-neutral heat energy in buildings. Smart city technologies clearly provide opportunities for emissions reduction city-wide, beyond the level of individual buildings.



Source Ministry of Land, Infrastructure and Transport, 2018

Recently, South Korea's Ministry of Land, Infrastructure and Transport (MOLIT) presented its new smart city plan, which includes four major promotion strategies:

1) disseminating a sustainable spatial model
2) establishing an AI/data-centric city foundation
3) building a private sector-friendly industrial ecosystem
4) activating the overseas expansion of K-smart cities

In particular, the K-City Network Overseas Demonstration Project, which supports overseas exports by companies in the smart city field and smart city development in overseas cities based on government cooperation in building a global network, has been initiated and selected six cities or regions for cooperation: Hue, Vietnam; Jakarta, Indonesia; Puerto Princesa, the Philippines; Siem Reap Province, Cambodia; Verona, Italy; and New Jersey, U.S.A.

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10. Coupling

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This chapter explores and assesses potential couplings between industry sectors that have the potential to reduce GHG emissions. Exchanging heat (thermal energy), steam, hydrogen and bioenergy are given primary attention, with CO_2 management (including CCS and CCUS) a potentially shared sector responsibility.

Successful coupling requires supply and demand to be matched even under variable conditions, thus necessitating system-wide management, storage and alternate supplies. This chapter also pays special attention to opportunities and challenges related to electrification as an enabler to decarbonise the industry sectors.

> *Coupling refers to the interaction between industry sectors where agents such as thermal energy, steam, hydrogen, bioenergy, CO_2 and other materials are exchanged between sectors.*

Coupling of energy between sectors already takes place and is expected to increase in the future, thereby leading to a system of coupled systems.[1,2] Coupling of sectors can offer several benefits and opportunities, including reduced GHG emissions, increased energy efficiencies, and lower total costs.

Although coupling of sectors offers these valuable benefits, its wider and final disposition might also pose important challenges. These include the need for enhanced coordination and communication between industry sectors, breaking down siloed thinking, and minimising financial risks arising from one or more sector participants. Another challenge is the development of technologies and management systems that enable coupling.

Overarching challenges include regulations and policies enabling smart coupling, social acceptance and education, not only for younger generations but also lifelong learning by current professionals.

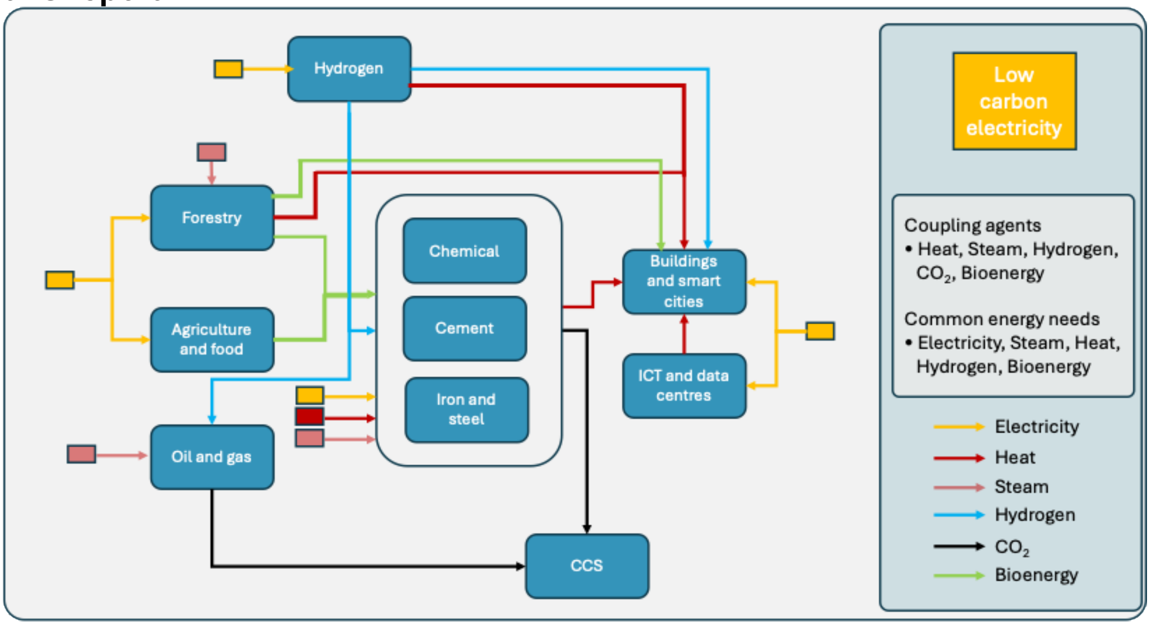
The following table summarises the potential benefits and challenges of coupling.

Potential benefits	Challenges
• Reduced sector and total GHG emissions • Increased sector and total energy efficiencies • Reduced sector and total system costs • Reduced dependence on external suppliers	• Technological readiness • Balancing material and energy flows • Managing technical and financial risks • Siloed thinking by sector participants • Enabling regulations, policies, social acceptance and education

Coupling between industry sectors in this report

Coupling opportunities for the industry sectors addressed in this report are shown in Figure 10.1. The following sections outline potential coupling between sectors and illustrate the potential benefits and challenges.

Figure 10.1: Actual and potential coupling of industry sectors addressed in this report



https://www.nature.com/articles/s41467-024-49867-w#Fig1

Heat as a coupling agent

Figure 10.1 visualises that thermal energy, especially in the form of excess low-grade or low-temperature heat generated by industry sectors such as chemicals, cement, forestry, data centres and electrolytic hydrogen plants, can potentially be used to heat buildings (through district heating systems) or by other industries located in the same industrial clusters.

District heating infrastructures can efficiently absorb, store and distribute heat and have already been implemented in several countries with colder climates.[3] For example, at the EU level, district heating constitutes around 12 percent of final energy use for space and water heating, where 43 percent of the heat supplied stems from renewable or waste sources.[4] Furthermore, excess heat from cement production can be used in today's district heating systems.[5] Similarly, utilising excess low-grade heat from hydrogen or low-carbon fuel production has been studied, where the excess heat can be used in district heating systems[6,7] or for nearby industries or industrial clusters.[8]

Steam as a coupling agent

Steam is widely used in the oil and gas, chemical and forestry industries and to a lesser extent in the iron and steel and cement industries. Steam coupling can be achieved by centralised or shared steam production. In fact, many industrial clusters already have central steam plants, with steam serving as a key coupling agent today and well into the future beyond 2040.

Hydrogen as a coupling agent

Figure 10.1 shows hydrogen being supplied to several industry sectors as well as oil and gas and smart cities. As described in the hydrogen chapter of this report, hydrogen and its derivatives (like ammonia or methanol) are likely to become key contributors to the energy transition, particularly in decarbonising hard-to-abate industry segments, such as long-haul aviation and shipping, high-temperature industrial processes and iron and steel. Furthermore, hydrogen is also foreseen to play important roles in the production of current and future high-value chemicals and in cities moving away from natural gas.[9] Many examples of small-scale electrolysers already exist today; examples can be found in an IEA database.[10]

Due to its multiple applications and the need to decarbonise hard-to-abate industrial sectors, hydrogen is expected to play prominent roles in the future beyond 2040. Presently, hydrogen is mainly produced near the demand site. In the future, a potential hydrogen infrastructure can support the scale-up of hydrogen production[11,12,13] and enable transport from cheaper production locations to larger demand centres. However, long-term planning (beyond 2040) for such new energy infrastructure will require enhanced and holistic coordination between energy carriers, e.g., electricity, methane and hydrogen, over long distances and across international borders.[14]

CO_2 as a coupling agent

Carbon dioxide from the oil and gas and other industry sectors (including cement, chemicals, and iron and steel) is a topic that requires attention to achieve global energy and climate targets. CCUS is therefore expected to play a key role in the future, with an increasing role beyond 2040.[15] Carbon can be captured from fossil fuels, fuels of biogenic origin, from the atmosphere or from processes such as the heating of limestone in cement manufacture. In particular, sustainable biogenic carbon will become scarce in a carbon-neutral future, and thus must be usefully deployed where urgently needed.

Biomass as a coupling agent

Biomass from the agriculture and food and forestry sectors is an energy and mass coupling agent. Biomass (e.g., wood pellets, wood waste and residues from agriculture and forestry) can be used by different industry sectors as a source of energy for heat, steam and electricity while also serving as feedstocks for the production of clean or low-carbon fuels (e.g., aviation fuels for long-haul flights), plastics and wood products (see the chapter on forestry). The increasing demand for biomass to support the decarbonisation of various sectors may lead to a situation where sustainable biomass becomes a scarce resource, which will require more attention in the future.

Electrification and coordination as enablers of the energy transition

The energy system is transitioning toward higher shares of variable renewable energy sources to reduce GHG emissions and comply with climate pledges. At the same time, the energy system is becoming increasingly coupled across sectors and infrastructures (electricity, heat, gas). Increased sector coupling requires a holistic and coordinated view when making investment decisions, both for energy generation and infrastructure and to ensure optimal operation and management of the different sectors and systems. Holistic and coordinated long-term planning, even beyond 2040, for investment in new energy generation and infrastructure across carriers (e.g., electricity, gas and hydrogen) and countries is therefore a focus point that requires attention.[16]

Increased couplings of energy systems can be facilitated by, for example, electrification in various forms: power-to-heat, power-to-mobility, power-to-gas, and power-to-chemicals.[17,18,19,20,21,22] Electrification, in combination with other methods, offers an important opportunity to help decarbonise sectors that have relied heavily on fossil fuels in the past (including transportation, buildings and industry). Electrification is therefore seen as a key enabler of the energy transition and is an essential component of future power systems.

However, variable renewable electricity generation is characterised by its fluctuating and stochastic nature; it has relatively low-capacity factors. This means potentially massive perturbations in the electric power system, which will sometimes produce too much electricity and sometimes not enough (e.g., in periods of low wind or sun, cold spells, major storms, etc.). This is a major challenge for electric power systems, with these systems occasionally “begging” for offtake and flexibility.[23] Their flexibility needs can be addressed with options such as peak generation, transmission, storage and demand-side flexibility/management. All of these constitute major challenges for facilitating the integration of larger shares of variable renewable energy required for the transition of the power system.

Perspectives on engineering and general management of coupled industry sectors

This chapter has highlighted the opportunities and addressed some of the challenges related to the complexity of coupled sectors, systems or plants.

The complexity of the general management of coupled industry sectors includes different owners, different maintenance and refurbishment schedules, different employment or union contracts, differences in proximity between producers and users, and different expectations for financial returns. Therefore, addressing these challenges requires special skills that may not be present in any one plant or company. This leads to the need for relevant education and computer models that enable performance validation and change estimates.

Future engineers must be educated at universities and colleges and engage in lifelong learning to solve the challenges of tomorrow's society and industries, including the urgent transition of sectors and systems toward a low or zero-GHG emissions world. Furthermore, interdisciplinary collaboration between engineers, technicians, specialists and other experts in different fields, such as economics and political science, is important to facilitate a just, cost-efficient and sustainable transition of our society. While specialists in various fields must urgently develop and explore new discoveries (technologies, software, etc.), a strong understanding of the potential couplings, synergies and interactions between plants, sectors and systems will be urgently needed beyond 2040, requiring effort and thought about how to best equip future personnel with the competencies to tackle and solve future challenges associated with transitioning industry sectors through clean technologies and coordination and coupling of sectors and systems.

Strategies that should be adopted to enable stronger couplings between industry sectors

- **Increasing coupling and coordination between industry sectors by breaking down siloed thinking.**
  Coupling different industry sectors can potentially lead to increased energy efficiency, reduced GHG emissions and lower systems costs. Seizing these opportunities should be a high priority when planning for a sustainable future beyond 2040.

- **Known technologies that enable coupling between sectors must be readied for scale-up toward and beyond 2040.**
  Many technologies are known today: for example, electrolysers, power-to-heat or mobility and CCUS. While these technologies are expected to play a key role in the future, scale-up is required to get on track toward a low or net-zero GHG emissions society beyond 2040.

- **Electrifying industry sectors to enable a sustainable transition.**
  Electrification is the preferred option when electricity is generated by clean technologies. Clean or low-carbon fuels or gasses should be used in hard-to-decarbonise sectors where no alternatives are (technically or economically) available.

- **Enabling couplings between industry sectors and systems requires:**
  i. **Coherent regulations and policies that support the implementation of smart and coupled sectors.**
     Regulations and policies are vital to support implementation of new solutions and are required to facilitate the scale-up of technologies (electrolysers, CCS, etc.) and infrastructure (electricity, hydrogen), all of which are urgently needed now and beyond 2040.

ii. **Acceptability, including social acceptance and fair and acceptable sharing between coupled sectors.**
Social acceptance: Increased electrification requires large-scale investments in and installations of new, clean electricity generation capacity and energy infrastructure. This, in turn, means that the public needs to accept and support the installation of corresponding infrastructure and systems, such as onshore wind, solar PV, nuclear, CCUS, gas and chemicals storage, and cross-country energy transmission.

Fair and acceptable sharing of burden between coupled plants/sectors: Properly coupled plants would lead to lower total GHG emissions and greater energy efficiencies than the sum of standalone plants. Furthermore, CCS and CCUS become more viable, technically and economically, with proper coupling between plants. However, a downside of coupled plants is that some problems, such as emissions, become much more difficult to attribute to any one plant, and the total emissions in specific geographic areas may increase. These issues will require special attention in the future.

iii. Education of younger and next-generation citizens and life-long learning by professionals.
The complexity of coupling plants or sectors introduces new challenges that require special skills, which can be acquired through coordination or collaboration between plants or sectors and fostering interdisciplinary collaboration. Future engineers will need to master new holistic and sector- or system-wide competencies, so they can tackle and solve the future (beyond 2040) challenge of transitioning industry sectors by means of clean technologies and coordination and coupling of sectors and systems.

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Conclusions

This report used the foresight approach to answer the following focal question:

> **What actions need to be taken now, and in the near future, so that sufficient technologies are available and realistically deployable to ensure low-GHG emissions from energy use in selected sectors beyond the year 2040?**

GHG emissions unrelated to energy use in these industry sectors were also considered.

Important advances are needed beyond those identified in the 2022 report of the CAETS Energy Community, *Towards low-GHG emissions from energy use in selected sectors*.[1] In many cases, these advances are already in progress, but require refinement, scale-up, and efficiency improvements to meet sustainability and economic objectives. In other cases, new engineering processes and products remain to be conceptualised and evaluated. Detailed strategies to achieve the objectives are presented in the individual chapters. The following summary presents the key strategies for the various sectors at a high level, with the reader being referred to the chapters for further details.

Forestry industry:	• Enhance forest value and carbon storage • Develop sustainable, circular products • Maximise use of residuals • Ensure availability of expert personnel
Agriculture & food industry:	• Widen understanding of terrestrial ecosystems and the roles of agriculture • Support farmers to mitigate GHG emissions and recycle nutrients, water and energy • Enhance use of digital technologies and AI, and increase international collaboration
Oil & gas industry:	• Explore the use of small modular refineries when special conditions apply • Increase electrification of major process units and use of hydrogen • Prepare for evolving product demands, including from the chemical industry • Continue to reduce emissions • Capitalise on opportunities in the natural gas and liquified natural gas sectors
Hydrogen	• Accelerate, optimise and increase stability of green hydrogen production, especially by means of electrolysis • Develop expertise and expand understanding of the formation and production of geologic hydrogen • Evaluate the viability of and pursue commercial-scale geologic hydrogen production by locating suitable deposits of magnesium–iron silicates followed by stimulation with water or brines

Carbon capture & storage (CCS):	• Rapidly increase current CCS deployment rates, including technology cost reductions • Increase Technology Readiness Levels of CCS process technologies • Use international collaboration to minimise unnecessary duplication efforts • Provide clear and stable policies, regulations and incentives
Chemical industry:	• Identify, develop and produce new chemicals that meet sustainability and market criteria (including new plastics and inorganics for electric vehicles), and improve recyclability of final products • Accelerate production of major energy carriers, including NH_3 and H_2 • Develop new catalysts and processes, especially electrochemical processes • Use green hydrogen as a raw material, reducing agent and/or fuel
Cement industry:	• Innovate materials and manufacturing, including advanced chemistries and electro-chemical processes, while adapting to changing market demands • Standardise durability and long-term performance assessment approaches and implement policies to incentivise sustainability • Accelerate shift to non-fossil energy sources • Utilize Grand Challenge approaches to accelerate innovation
Iron & steel industry:	• Boost H_2 utilisation in blast furnaces and accelerate alternative H_2-based processes • Electrify key process units (EAF, ESF) to cut carbon intensity • Adapt to new product demands (e.g., COASTALUME, high-Mn TWIP) • Maximise circularity by recycling by-products and scaling next-gen electrolytic processes
Buildings & smart cities:	• Promote active citizen and decision-maker engagement • Adapt to climate change-driven extreme weather impacts (floods, heat, etc.) • Create resilient water and energy systems that are sustainable and affordable • Modernise public and private building stocks
Coupling:	• Increase inter-industry coupling and coordination

- Improve policies, social acceptance and education surrounding coupling
- Scale up known technologies and electrify sectors

A separate paper will be published on the ICT & data centres sector. Changes in this sector are occurring so rapidly that an assessment using the foresight approach with a time horizon beyond the year 2040 was deemed to be impractical.

The following overarching strategies, which can be adopted by all sectors, were identified:

- Ensuring a well-educated, knowledgeable citizenry that will support the introduction and use of policies, products and processes aimed at meeting sustainability objectives.

- Maintaining and expanding an expert workforce capable of conceptualising and implementing new products and processes. This will require stronger and better-resourced educational institutions and research centres of excellence and heightened collaboration among industry, academia and government.

- Implementing policies, regulations and practices, including incentives and taxation measures, that are more supportive of accelerated process and product innovation.

- Intensifying collaboration at the national and international levels to accelerate development and adoption of products and processes without prohibitive trade barriers and subsidies.

- Using digitisation and artificial intelligence to create and implement these changes.

- Accounting for regional and national characteristics and differences, levels of general and economic development, and the capital-intensive nature of these industry sectors.

Intent and future work

The CAETS Energy Community did not develop this report with the intent of being prescriptive, but rather to engage readers in considerations and actions appropriate for their industry sectors and national realities. As the work neared completion, two additional general conclusions were reached:

- Artificial intelligence tools could be used to gain additional insights into industry characteristics, possible strategies and potentially attainable results. Preliminary indications were promising; however, they also suggested that considerably more work is needed beyond the scope of the Sequel Project to harmonize AI insights with engineering fundamentals and local conditions.
- A greater understanding of energy security is needed, including energy affordability for end users. A new project to support this need has been initiated by the CAETS Energy Community under the leadership of the Indian National Academy of Engineering (INAE).

Reference

[1] International Council of Academies of Engineering and Technological Sciences (CAETS), *Towards low-GHG emissions from energy use in selected sectors* (University Park, MD: CAETS, 2022), accessed June 21, 2024, https://www.newcaets.org/wp-content/uploads/2023/02/CAETS-ENERGY-REPORT-2022-22-January-2023.pdf.

Glossary of select terms

AD – anaerobic digestion

AEL – liquid alkaline electrolyte

AEM – anion exchange membrane

AgTech – agricultural technology

AI – artificial intelligence

ASTM – American Society for Testing and Materials

ATES – aquifer thermal energy storage

bbl/d or bpd – barrels per day (of oil)

BECCS – bioenergy with carbon capture and storage

BEMS – building energy management systems

BF – blast furnace

BF-BOF – blast furnace–basic oxygen furnace

BOF – basic oxygen furnace

BIF – banded iron formations

BTES – borehole thermal energy storage

BTX – benzene, toluene, and xylene isomer mixtures (hydrocarbons)

CAE – Canadian Academy of Engineering

CAETS – International Council of Academies of Engineering and Technological Sciences

CBAM – carbon border adjustment mechanism

CCS – carbon capture and storage

CCUS – carbon capture, utilization and storage

CCU – carbon capture and utilization

CDR – carbon dioxide removal

CLC – calcium looping combustion

COG – coke oven gas

COP26 – 26th Conference of the Parties

Course50 – CO_2 Ultimate Reduction System for Cool Earth 50

CSA – Canadian Standards Association

DAC – direct air capture

DOE – U.S. Department of Energy

DR – direct reduction

DRI – direct reduced iron

EAF – electric arc furnace

EDI – equity, diversity and inclusion

EGR – enhanced gas recovery

EJ – exajoule (10^{18} joule)

EOR – enhanced oil recovery

EPD – environmental product declaration

ESF – electric smelting furnace

GCC – global carbon cycle

GCCSI – Global Carbon Capture and Storage Institute

GenAI – generative artificial intelligence

GHG – greenhouse gas

GI – green innovation

GJ – giga joule (10^9 Joule)

GJ/t – giga joule per tonne

GTonne/Gt – giga tonne (10^9 tonne)

GREINS – Green Innovation in Steelmaking

GW – giga watt (10^9 watt)

GWP – global warming potential

HEMS – home energy management systems

HHV – higher heating value

HIsmelt – high intensity smelting

HVAC – heating, ventilation, air conditioning

HYBRIT – hydrogen breakthrough ironmaking technology

HyCROF – hydrogen-enriched carbonic oxide recycling oxygenate furnace

HyREX – hydrogen reduction ironmaking technology iACRES – smart ironmaking process based on active carbon recycling energy system

ICT – information and communications technology

IoT – internet of things

IEA – International Energy Agency

IEAGHG – International Energy Agency Greenhouse Gas R&D Programme

IPCC – Intergovernmental Panel on Climate Change

JFE – Japan Steel Engineering/Japan Future Enterprise

JRCM – Japan Research and Development Center for Metals

Kg/tHM – kilogram per tonne of hot metal

LC3 – limestone calcined clay cement

LED – light emitting diode

LOHC – liquid organic hydrogen carrier

LNG – liquefied natural gas

MEA – monoethanolamine

MEG – monoethylene glycol

MOE – molten oxide electrolysis

MOLIT – Ministry of Land, Infrastructure and Transport (South Korea)

MJ – megajoule (10^6 joule)

Mt – megatonne (million tonne or 10^6 tonne)

MTPA – million tonnes per annum

Mt/y – million tonnes per year

MWh – megawatt-hour

MWh/t – megawatt-hour per tonne

NASEM – National Academies of Sciences, Engineering and Medicine

NDC – national determined contribution

NG – natural gas

OECD – Organisation for Economic Co-operation and Development

PEM – proton exchange membrane

PERED – Persian direct reduction technology

PV – photovoltaic

ROK – Republic of Korea

SCM – supplementary cementitious materials

SOE – solid oxide electrolysis

SOEC – solid oxide electrolysis cell

STP – standard temperature and pressure (0ºC, 101.325kPa)

t/m^3/d – tonnes per cubic metre per day

Toe/yr – tonnes of oil equivalent per year

TRL – technology readiness level

TWIP – twinning-induced plasticity (steel-Mn alloy)

ULCOLYSIS – ultra-low CO_2 steelmaking and electrolysis

ULCOS – ultra-low CO_2 steelmaking

ULCOWIN – low-temperature electrowinning for steelmaking

UN – United Nations

UNFCCC – United Nations Framework Convention on Climate Change

USGS – United States Geological Survey

WECCS – waste energy with carbon capture and storage

3D – three-dimensional