IMPACTS OF EMERGING INDUSTRIES AND BUSINESSES

Hydrogen, Carbon Capture Utilisation and Storage, and Artificial intelligence

United Nations Climate Change
Katowice Committee on Impacts

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Hydrogen, Carbon Capture Utilisation and Storage, and Artificial intelligence

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Impacts of emerging industries and businesses: hydrogen, carbon capture, utilization and storage, and artificial intelligence

Mandate description

This work is an output of the implementation of activity 5 of the workplan of the forum on the impact of the implementation of response measures and its Katowice Committee of Experts on the Impacts of the Implementation of Response Measures[1].

Activity 5: Build awareness and understanding of Parties and other stakeholders to assess the economic impacts of potential new industries and businesses resulting from the implementation of response measures with a view to maximizing the positive and minimizing the negative impacts of the implementation of response measures.

Acknowledgement

The Katowice Committee of Experts on the Impacts of the Implementation of Response Measures extends its appreciation to the observers who provided inputs for preparing this report. The individuals below contributed in their expert capacities and their affiliations are only mentioned for identification purposes.

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[1] As contained in annex II to decisions 4/CP.25, 4/CP.15 and 4/CMA.2.

FOREWORD

by Catherine Goldberg and Peter Govindasamy, Co-chairs of the KCI

The Katowice Committee of Experts on the Impacts of the Implementation of Response Measures is deeply committed through our work in supporting the Paris Agreement temperature goal of holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels. In this regard, we believe that new low emission strategies such as Hydrogen, Carbon Capture, Utilization and Storage (CCUS), complimented by the use Artificial Intelligence (AI), will have a significant role in global mitigation efforts, alongside other decarbonization strategies.

Even as Parties and other stakeholders must bolster efforts towards the development and readier access to these technologies, there is also an immediate need to build awareness and a foster a clearer understanding of these tools. This publication seeks to fill this knowledge gap by providing a detailed description of hydrogen, CCUS and AI, methods to assess the economic and social impacts of these technologies, and the imperative of maximizing the positive and minimizing the negative impacts of implementation of response measures.

Among other salient points, the publication reinforces the point that these technologies offer significant positive opportunities. These include the creation of sustainable jobs, skills and knowledge, and the avoidance of stranded assets and extension of the lifespan of existing infrastructure – all of which can increase prosperity for workers, provide stable employment and boost clean economic growth. In addition, there is also scope for substantial flow-on effects and high-value spill overs that stimulate innovation-led growth.

All in all, this publication will support the work of the Forum on the Implementation of Response Measures and can also serve as a resource for the Mitigation Work programme and the just transition work programme.

Catherine Goldberg
Co-chair, KCI

Peter Govindasamy
Co-chair, KCI

PREFACE

by Senior Director Daniele Violetti, Programmes Coordinator, UNFCCC

In the midst of climate change challenges, innovation and informed decision-making are crucial. Innovations around the world are leading to new industries and businesses - creating new opportunities and threats – and increasing the need for informed decision. This document, created by the Katowice Committee on Impacts (KCI), explores the impacts and potential of emerging industries resulting from climate change mitigation policies, also known as response measures. It provides valuable insights to policymakers, researchers, and everyone involved in designing policies and taking actions to address climate change through deep decarbonization, in line with sustainable development objectives.

Using various methodological approaches, the authors review relevant submissions, studies, and publications from UNFCCC, Parties, and other stakeholders. A comprehensive literature search and impact assessment form a credible framework for evaluating emerging industries and businesses.

The research focuses on industries that contribute to climate change mitigation efforts, with a focus on hydrogen, CCUS (Carbon Capture, Utilization and Storage), and AI (Artificial Intelligence). These industries were selected based on their potential for driving progress in limiting global temperature rise. Their applications and impacts are explored in-depth utilizing well-established methodologies like the levelized cost of carbon abatement and life cycle assessment. The scope includes social and environmental dimensions, aligning with sustainable development.

Achieving net-zero emissions requires efforts across the whole of economy, and hydrogen, CCUS, and AI offer versatile solutions, applicable also for fossil fuel-dependent economies and industrial facilities. I sincerely hope that this report will serve as a vital resource for understanding the potential, challenges, and opportunities of emerging industries in climate change mitigation. It will inform Parties' and other stakeholders' policy development and decision-making, and facilitate global, regional, and national actions towards a sustainable and resilient future, in line with the goals of the Paris Agreement.

Daniele Violetti
Senior Director
Programmes Coordination, UNFCCC

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ABBREVIATIONS AND ACRONYMS

AI	artificial intelligence
AR	Assessment Report of the Intergovernmental Panel on Climate Change
CCS	carbon dioxide capture and storage
CCUS	carbon capture, utilization and storage
CMA	Conference of the Parties serving as the meeting of the Parties to the Paris Agreement
CMP	Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol
CO_2	carbon dioxide
CO_2 eq	carbon dioxide equivalent
GHG	greenhouse gas
GOH	guarantee of origin for hydrogen
ICT	information and communications technology
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
KCI	Katowice Committee of Experts on the Impacts of the Implementation of Response Measures
LCA	life cycle assessment
LCCA	levelized cost of carbon abatement
PV	photovoltaics
SMR	steam methane reforming

EXECUTIVE SUMMARY

There is overwhelming and compelling scientific evidence of the need for urgent and deep decarbonization. This evidence underpins the global efforts to implement climate change mitigation policies and measures (also known as response measures) that can significantly contribute to achieving global net zero GHG emissions. Governments and national stakeholders are preparing and implementing short-, medium- and long-term low-emission development strategies; however, some unintended impacts may arise as a consequence of implementing these climate change mitigation policies and actions. The impacts could be positive or negative, so identifying and addressing them is as important as implementing the mitigation policies and actions themselves.

This technical paper addresses activity 5 of the workplan of the forum on the impact of the implementation of response measures and its KCI: “Build awareness and understanding of Parties and other stakeholders to assess the economic impacts of potential new industries and businesses resulting from the implementation of response measures with a view to maximizing the positive and minimizing the negative impacts of the implementation of response measures.”[2]

In the context of this study, emerging industries and businesses are considered to be those productive entities (materials, goods and services) that do not have a fully matured operating ecosystem because they are at an early stage of development, but do have the potential to significantly contribute to the global deep decarbonization effort by changing the current trajectory of global GHG emissions towards net zero. An assessment of 65 industries and businesses, which were selected on the basis of the above-mentioned definition and scope, identified 3 industries that have significant GHG abatement potential and could contribute to meeting the global climate change mitigation goal of keeping the global temperature rise well within 1.5oC by 2050.

The three emerging industries and businesses are production and use of hydrogen; carbon capture, utilization and storage (CCUS); and use of artificial intelligence (AI). Extensive analysis and assessment were carried out to understand how these technologies could be deployed in combinations that would enhance their applicability and usefulness, while remaining generally consistent with the theory of change principles and sustainable development imperatives.

This paper advocates that reaching net zero emissions by 2050 demands deep decarbonization worldwide, meaning that all economies – big and small – will need to contribute towards this goal using available technologies. In doing so, countries will need to consider how their national natural resources can contribute to the change required. The opportunity for all countries in all regions to contribute to the global mitigation goal, leaving no one behind, can be made possible by taking advantage of the versatility of hydrogen, CCUS and AI, and by deploying these technologies in novel ways. The tremendous potential that hydrogen and CCUS provide can be further enhanced by using AI on a massive scale.

Assessing the social, economic and environmental impacts of emerging industries and businesses is important for raising awareness and understanding among all stakeholders of their benefits or otherwise to society and towards achieving global climate change mitigation goals. In particular, the impacts of climate change mitigation policies can arise before or after implementation, so it is crucial to design and implement only appropriate and impactful national-level policies and measures.

Having a clear understanding of the impacts is also important when choosing the impact assessment methods and tools. Depending on the depth and complexity of the assessment study, several methods could be used, either individually or in combination.

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[2] As contained in annex II to decisions 4/CP.25, 4/CP.15 and 4/CMA.2.

The authors of this paper applied the LCCA impact assessment and LCA methods for the shortlisted industries and businesses, conscious of the fact that other more robust numerical assessment methods could, in the future, complement the current work. The LCCA and LCA methods are sufficient to provide the insights needed when raising awareness and understanding among policymakers, including to encourage them to adopt transformative solutions that go beyond a one-size-fits-all approach.

Existing literature offers insightful observations on the impacts of the three shortlisted emerging industries.

For example, hydrogen could deliver many gigatonnes (Gt) of abatement annually when used in various hard-to-abate industries, transport and stationary energy. The Hydrogen Council (2022) estimates that hydrogen demand could exceed 500 Mt by 2050, delivering up to 6 Gt of abatement per year. However, achieving that level of abatement requires an increasing demand and supply of green hydrogen. According to the Hydrogen Roadmap Europe (Fuel Cells and Hydrogen 2 Joint Undertaking, 2019), the global energy transition to net zero emissions by 2050 cannot be achieved without deploying hydrogen fuel on a large scale. A major benefit of hydrogen is that it is a versatile, clean and flexible energy vector. It allows for large-scale integration of renewable energy sources because it enables energy providers to convert and store renewable energy as a gas. The most advanced and matured technological pathways for hydrogen production are methane steam reforming, biomass gasification, and hydrolysis.

CCUS is crucial to climate mitigation because it can provide significant point source emission reductions in energy-intensive sectors. The contribution of Working Group III to the Sixth Assessment Report (IPCC, 2022) highlighted that removing carbon from the atmosphere through CCUS is a key part of keeping within the 1.5 and 2°C global warming target and further states that, alongside drastic cuts in emissions, “negative emissions” technologies are likely to be a necessary part of the transition to net zero. These technologies capture the CO_2 emitted by major sources such as fossil fuel power plants, allowing the CO_2 to be used or safely stored.

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Further, the AR6 (IPCC, 2022) warns that without CCUS, the world's fleet of coal and gas plants would need to be retired 23 and 17 years early, respectively, to keep emissions low enough to restrict global warming to between 1.5 and 2°C. The AR6 warns: "Practically all long-lived technologies and investments that cannot be adapted to low-carbon and net zero emission modes could face stranding under climate policy." It suggests that carbon-intensive facilities could be adapted by pairing them with CCUS technologies to prevent them from becoming "stranded assets" prematurely, which would increase transition costs and reduce public acceptance.

Significant deployment of CCUS is critical to lowering the costs of applying this technology. The analysis by the *Energy Technology Perspectives Special Report 2020* (IEA, 2020) concluded that CCUS is the only group of technologies that directly contributes to both reducing emissions in key sectors and removing CO_2 to balance emissions that cannot be avoided. This is a critical part of reaching net zero targets and illustrates why reaching net zero will be virtually impossible without CCUS. In addition, CCUS is one of the two main ways to produce low-carbon hydrogen, which is crucial for future energy needs.

Climate change is a disruptive system that is affecting all sectors of the global economy, irrespective of geography and capacity. Dealing with the problem of climate change requires system thinking and the use of cognitive science, which can be provided in part by AI. The application of AI could significantly augment the efforts of governments, businesses and other stakeholders in abating GHG emissions and adapting to climate change impacts. AI is an enabler of new and emerging industries and businesses at scale: it offers reliability and cost-effectiveness, and it can solve complicated problems and make decisions. Using AI combined with physical equipment and systems can reduce energy use and carbon emissions across the economy, including in the power, transportation, buildings, industry and agriculture sectors.

The social, economic and environmental impacts of the three shortlisted emerging industries and businesses (hydrogen, CCUS and AI) are varied: some positive and some negative. However, the positive impacts arising from the deployment of these technologies far outweigh the negatives.

The positive social, economic and environmental impacts of deploying CCUS include creation of sustainable jobs, increasing skills and knowledge, and the ability to avoid stranded assets and extend the lifespan of existing infrastructure – all of which can increase prosperity for workers, provide stable employment and boost clean economic growth. In addition, there may be substantial flow-on effects and high-value spillovers that stimulate innovation-led growth. Deploying CCUS also offers economy-wide pathways to net zero emissions and widens the range of abatement costs. CCUS helps avoid CO_2 point source emissions, decreases atmospheric CO_2 emissions and can improve air quality.

On the other hand, there are negative impacts of CCUS, such as (1) the difficulty of achieving societal acceptance owing to risk–benefit perceptions and information provision (especially related to leakage); (2) the potential increase in electricity costs; and (3) the link with water stress owing to additional demand for chemical and physical processes to capture and separate CO_2 in CCUS-fitted thermoelectric and fossil-fuel thermal power systems, as well as the parasitic load imposed by CCUS in power plants which tends to reduce their efficiency, and the potential for groundwater contamination in geological sequestration which could affect underground water quality.

Hydrogen production and use also comes with widely acknowledged social, economic and environmental benefits. These include the potential for positive transformational changes in societal structure; improvements in air quality due to the use of this cleaner fuel; creation of sustainable, decent and quality jobs; increases in capacity and knowledge arising from reskilling and retooling of existing jobs; reduction of inequality among nations in terms of national natural resources that can make countries even more energy independent and energy secure; improvements to gender equality and empowerment; and integration with low-carbon alternatives in the energy, transport and industry sectors. Other benefits include promoting industries and revitalizing regional economies through patents relating to hydrogen technology; use and rescheduling of the decommissioning of existing gas infrastructure in countries where this exists, enabling large-scale, efficient renewable electricity integration owing to the intermittent character of solar and wind, and electricity systems; decarbonizing industrial energy use; serving as a feedstock for industry; stimulating new businesses and investments; reducing resource dependency; cutting energy costs and improving citizens' lives and air quality; and facilitating and stimulating global economic growth and promoting the circular economy and industrial eco-symbiosis.

The use of hydrogen is a long-term option for reducing CO_2 emissions and a huge opportunity for reaching the global warming goal under the Paris Agreement. Hydrogen can largely reduce environmental stress because if it is used to produce energy no CO_2 is emitted. Using hydrogen will reduce pollution levels in cities and urban centres, which has become a key concern for many governments and local authorities.

If large quantities of hydrogen can be produced at competitive costs and without undue carbon release, hydrogen would offer marked advantages compared with other secondary fuels, because hydrogen is likely to burn more cleanly in combustion engines and is better matched to fuel cell use than competing fuels.

Use of hydrogen technology also comes with some negative impacts such the "hydrogen warming" impact. In particular, the climate consequences of deploying hydrogen compared with fossil fuels strongly depend on time horizon and leakage rate. Also, other externalities associated with hydrogen production, such as parasitic load during production and loss of energy during the conversion of hydrogen, could decelerate technology implementation if not carefully addressed.

There are wide social, economic and environmental benefits of using AI. The economic returns of AI are achieved through creating employment, improving quality of life and enabling the adoption of green technologies. Digitalization/AI can also contribute to economic growth and reduce GHG emissions. In the energy sector, AI/digital technologies have the versatility to improve wind and solar generation forecasts and to help maximize performance of power grids. In other sectors, AI could deliver e-health services to billions of people, and it can contribute to smart agriculture, manufacturing including virtual manufacturing, customer-centric production, circular supply chains and smart services across the developing and developed world. AI technologies can enhance communications between electricity generators and consumers and implement flexible demand response strategies to better align use with resources.

One of the most obvious applications of AI to climate change is its potential to improve climate modelling and predictions. AI can be part of the solution in any application, or a combination thereof, for policies and measures that aim to address climate change. It is a tool that enables other tools and abatement methods to function optimally across all fields.

However, while embracing AI as part of the climate strategy, it is important to be aware of the trade-offs associated with it. As with all emerging technologies, AI may face uncertainity, high upfront costs and scrutiny by regulators. Application and use of AI technologies can also increase carbon abatement costs, and AI can be a large consumer of electricity.

Maximizing the positive and minimizing the negative impacts associated with these emerging industries and businesses will require government intervention and extensive stakeholder cooperation.

For CCUS, such interventions include developing a regulatory framework for CO_2 capture, transport, utilization and storage at the national or global level. A framework will help ensure standardization of the design and application of CCUS, coupled with high safety standards. Strengthening policy support for CCUS to drive innovation and deployment is central to the scaling up of CCUS. As CCUS technologies mature, specific policy incentives will be crucial for expanding the frontier of the market around the world.

For hydrogen, the mega funds that have been ring-fenced for climate technologies, such as Brookfield's USD 7 billion Global Transition Fund and TPG's USD 5.4 billion Rise Climate Fund, can be made accessible to developing countries to support hydrogen economy programmes. There is a need for collaboration on adopting a uniform methodology for calculating life cycle GHG emissions for hydrogen, and on developing comprehensive and science-based terminology, as well as standards, codes and best practices for hydrogen fuel deployment; and there is a need to expand collaboration on sustainable hydrogen production across all regions, as well as the developing a sustainable hydrogen market through market stimulation programmes.

Other aspects of government, private sector and other stakeholder engagement on hydrogen fuel include the development of a tradable GOH to decouple physical from commercial flows and accelerate hydrogen deployment worldwide, as well as the development of bespoke institutional capacity-building and training packages to support the transition to the hydrogen economy. This will involve developing the necessary systemic, legal and regulatory frameworks; undertaking scientific assessments to pin down the national resource endowment potential for sustainable hydrogen production; developing systems for sustainable and transformational impacts monitoring, reporting and verification consistent with the enhanced transparency framework under the Paris Agreement; supporting research and development as well as knowledge management infrastructure to promote peer-to-peer learning; and undertaking economic and financial analyses, including assessment of diversification of investments and business models for investment in the hydrogen economy. In addition, there is the need to promote partnerships in support of the production and use of hydrogen involving relevant national and international stakeholders from the public and the private sectors, as well as from civil society and research and academia.

Using AI to address the overwhelming climate challenge can be assisted by promoting inter- and intra-country learning, including by identifying relevant skills; optimizing existing knowledge and capabilities; and developing new skills through targeted training. In addition, it will be important to foster collaboration among all stakeholders, such as undertaking joint pilot activities and programmes, and listening to and sharing knowledge and data sets from governments (policymakers), business communities, research and academia, AI experts and civil society groups; and consciously and systematically implementing and deploying AI tools to achieve the desired impacts.

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1

INTRODUCTION

1.1. Mandate of the Katowice Committee on Impacts

The COP, the CMP and the CMA each adopted decisions on the functions, modalities and work programme for the forum on the impact of implementation of climate change mitigation policies and measures[3], (often referred to as response measures) at their sessions in Katowice, Poland, in December 2018.[4] The CMA, by its decision 7/CMA.1, established the KCI to assist the forum in the implementation of its work programme, which deals with all issues related to the impacts of the implementation of response measures under the Convention, its Kyoto Protocol, and the Paris Agreement. The forum has the following functions:

- **a.** Providing a platform allowing Parties to share, in an interactive manner, information, experiences, case studies, best practice and views, and to facilitate assessment and analysis of the impact of the implementation of response measures, including the use and development of modelling tools and methodologies, with a view to recommending specific actions;
- **b.** Providing recommendations to the subsidiary bodies on the actions referred to in paragraph (a) above for their consideration, with a view to recommending those actions, as appropriate, to the COP, the CMP and the CMA;
- **c.** Providing concrete examples and case studies of best practice, in order to enhance the capacity of Parties, in particular developing country Parties, to deal with the impact of the implementation of response measures;
- **d.** Addressing the effects of the implementation of response measures by enhancing cooperation among Parties, stakeholders, external organizations, experts and institutions; by enhancing the capacity and the understanding of Parties regarding the impacts of mitigation actions; and by enabling the exchange of information, experience and best practice among Parties to raise their resilience to these impacts;
- **e.** Responding and taking into consideration the relevant outcomes of different processes under the Paris Agreement;
- **f.** Promoting action to minimize the adverse impacts and maximize the positive impacts of the implementation of response measures.

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[3] The forum on the impacts of the implementation of response measures for brevity is hereinafter referred to as the forum.
[4] Decisions 7/CP.24, 3/CMP.14 and 7/CMA.1.

The above-mentioned decisions also adopted the following four areas for the work programme necessary to address and manage the impacts of the implementation of response measures:

- Economic diversification and transformation;
- Just transition of the workforce and the creation of decent work and quality jobs;
- Assessing and analysing the impacts of the implementation of response measures;
- Facilitating the development of tools and methodologies to assess the impacts of the implementation of response measures.

1.2. Mandate for the technical paper

COP 25 adopted a detailed workplan (with deliverables and timelines) for implementing the four areas of the work programme.[5] This workplan mandated the KCI to prepare a technical paper to address activity 5 of the workplan: "Build awareness and understanding of Parties and other stakeholders to assess the economic impacts of potential new industries and businesses resulting from the implementation of response measures with a view to maximizing the positive and minimizing the negative impacts of the implementation of response measures."

1.3. Objectives of this paper

The IPCC Sixth Assessment Report (2022) included overwhelming and compelling scientific evidence of the need for urgent and deep decarbonization. This evidence underpins the global efforts to implement climate change mitigation policies and measures that lead to net zero GHG emissions. In response to this imperative, governments and national stakeholders are preparing and implementing short-, medium- and long-term low-emission development strategies.

These efforts have given rise to many innovative new industries, businesses and technologies that are aiding the implementation of these mitigation policies and measures. The effective implementation of these urgent climate change response measures demands that equally urgent attention be paid to addressing and managing the intended and unintended, and positive and negative impacts associated with and arising from implementation of these deep decarbonizations measures.

The purpose of this technical paper is to understand the impacts of emerging industries and businesses resulting from the implementation of climate change mitigation response measures with a view to maximizing the positive and minimizing the negative impacts thereof.

However, the narrow view of the mandate to consider only the economic impacts of emerging industries and businesses has been expanded to include social and environmental impacts. The revised scope of the assessment is to ensure a more comprehensive and coherent treatment of the subject and aligns well with the sustainable development concept of the "triple bottom line". The intention to include technology as the fourth dimension for impact assessment has been captured in the criteria for shortlisting emerging industries and businesses. This amplification of the mandate has thus resulted in the following objectives for this paper:

- Define what constitutes emerging industries and businesses in the context of deep decarbonization efforts and climate change mitigation in general;
- Enhance the awareness and understanding of stakeholders on emerging industries and businesses resulting from climate change mitigation policies and measures;
- Understand the social, economic and environmental impacts of these emerging industries and businesses;
- Explore ways to maximize the positive and minimize the negative impacts of these emerging industries and businesses by using appropriate methods and tools for assessing and categorizing these impacts.

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[5] Decision 4/CP.25.

2

METHODOLOGICAL APPROACHES

This chapter describes the methodological approach that underpins the research outcomes presented in chapter 3. It summarizes the context, the definition of emerging industries and businesses, the scope (considering the complete value chain from the up- to the downstream, allied industries and businesses) and the criteria for shortlisting particular industries and businesses. It also describes the extensive literature review, which involved an online search of peer-reviewed and grey publications. The study built on relevant work undertaken by other constituted bodies under the Convention and its Kyoto Protocol, and the Paris Agreement, including the work undertaken by KCI, as well as submissions from Parties and other stakeholders in response to the call for inputs by KCI.

2.1. Definitions

In macroeconomics, an **industry** is a branch of an economy that produces a closely related set of raw materials, goods or services. Although industries tend to be associated with specific products, processes and consumer markets, they can evolve over time. A **business**, on the other hand, is the activity of making a living or making money by producing or buying and selling products (such as goods and services), or simply “any activity or enterprise entered into for profit” (Burton, 2001).

An **emerging industry or business** is one that is in the early stages of development. The goods, service or technology that the emerging industry or business is developing may not be widely known by many people, and therefore may not have an operating ecosystem or a strong customer base (Corporate Finance Institute, 2023; Sunyaev, 2020).

This paper uses the following definition: emerging industries and businesses are those productive entities (materials, goods and services) that do not have a fully matured operating ecosystem because they are at an early stage of development, but do have the potential to significantly contribute to the global deep decarbonization effort by changing the current trajectory of global GHG emissions towards net zero.

2.2. Research methods

This paper was prepared using information gathered and synthesized through mixed methods, namely a desktop review, a systematic literature search, qualitative shortlisting and qualitative impact assessment.

As a result of using a combination of research methods, this technical paper thoroughly reflects the current understanding and diverse views on the potential of new and emerging industries and businesses in relation to the net zero emissions target; and it uses well-founded selection criteria and rationale for shortlisting those with the greatest impact potential. The combination of methods has resulted in a robust framework for assessing the economic, social and environmental impacts of the selected industries and businesses.

A brief overview of the methods is presented in this section.

Desktop review – This involved gathering and reviewing views on emerging industries and businesses contained in submissions by Parties to the UNFCCC, studies done by other constituted bodies including the Technology Executive Committee, and related publications, with a view to understanding and synthesizing their findings to inform the selected criteria and justifications for the shortlisting.

Systematic literature search – Over 100 literature sources including reports and peer-reviewed papers were consulted to obtain information for the study, many of which are listed in the references to this report. Publications were assessed on the basis of their relevance to the subject, how recently they had been published, their geographical focus and their scope of study. The literature search involved a comprehensive review of publications in academic and peer-reviewed journals and e-books to obtain a broad list of emerging industries/businesses. The search was made on the basis of the following criteria:

- Journals: identified through bibliographic databases including Science Direct, Web of Science, the *International Journal of Emerging Technology in Learning*, Scopus, Directory of Open Access Journals, Google Scholar, the Institute for Technology and Engineering's Inspec database, Portico, and Taylor and Francis;

- Constraints: search by year of publication, from 2000 to 2022;

- Keywords and search terms:

    - New industries and businesses arising from the implementation of climate mitigation policies and measures;
    - Climate change and new industries and businesses;
    - New and emerging industries and businesses;
    - New and emerging climate change relevant industries and businesses;
    - Climate change, new risks and opportunities for businesses;
    - New and emerging climate change mitigation relevant businesses and industries;
    - Climate change and new industries and businesses in 2022;
    - Emerging industries;
    - New industries and businesses;
    - New businesses and industries for climate change;
    - Top 20 new climate mitigation businesses;
    - Top 20 emerging climate mitigation industries;
    - New industries and businesses spring up due to climate change;
    - Emerging technology;
    - Socioeconomic and environmental impacts of hydrogen;
    - Socio-economic and environmental impacts of CCUS;
    - Socio-economic and environmental impacts of AI;
    - Top trends in technology 2022;
    - Top trends in business (business trends 2022);
    - New technology trends for 2022;
    - Top strategic technology trends for 2022;
    - Full economic cost and benefit analysis of hydrogen;
    - Hydrogen production and life cycle analysis;
    - CCUS and life cycle analysis;
    - Artificial intelligence and climate change.

The desktop review and the systematic literature searches produced a longlist of 65 emerging industries and businesses for implementing climate mitigation policies and measures relevant for the subsequent shortlisting.

Shortlisting of emerging industries/businesses – The industries/businesses identified from the literature search were assessed against a set of qualitative criteria to create a shortlist (see section 2.3.1). The shortlisting identified hydrogen, CCUS and AI as the key industries/businesses as the focus for the impact assessment in the next stage.

Qualitative impact assessment of shortlisted new industries/businesses – An assessment of the literature covering the three shortlisted emerging industries and businesses gathered information on their economic, social and environmental impacts. This technical paper presents a synthesis of the major economic, social and environmental impacts identified and the tools used for the assessment.

2.3. Scope of the technical paper

This paper focuses on emerging industries and businesses that help mitigate climate change by reducing or sequestering GHG emissions, and those that help understand climate change and its impacts through high-quality data processing and use. It does not cover new and emerging climate change adaptation technologies, industries and businesses.

In the context of climate mitigation, new and emerging industries and businesses may include but are not limited to hard and soft technologies that lend themselves to applications limiting GHG emissions, where "soft technologies" refers to skills (e.g. specialized skills for mobilizing finance through crowd funding and green bonds) and know-how, while "hard technologies" refers to tangible components such as equipment, tools, computers and software. In addressing the complexity of the climate emergency, which is the motive of this paper, a combination of both hard and soft technologies may be needed in new businesses and industries to address the climate change mitigation challenge.

According to Alairys et al. (2018) the "combined value delivered by multiple emerging technologies is multiplicative across sectors"; that is, "the impact on business innovation and the transformative effect of a combination of emerging technologies is far more profound than what a single technology can provide alone." This interaction is described as "the combinatorial effect of emerging technologies". The concept of combinatorial effect was therefore duly considered when selecting the emerging industries and businesses listed in this paper.

Emerging technologies include, but are not limited to, virtual reality (Merchant, 2010; Merchant et al., 2014), augmented reality (Dunleavy and Dede, 2014), mobile learning devices (Crompton et al., 2017), physical computing tools (Katterfeldt et al., 2018), "internet of things" hardware with sensors (Katterfeldt et al., 2018), and technologies that allow collaborative learning at a great scale (Cress et al., 2016). Table 1 lists some of the new and emerging technologies, industries and businesses suggested by the author and those discussed in the existing literature.

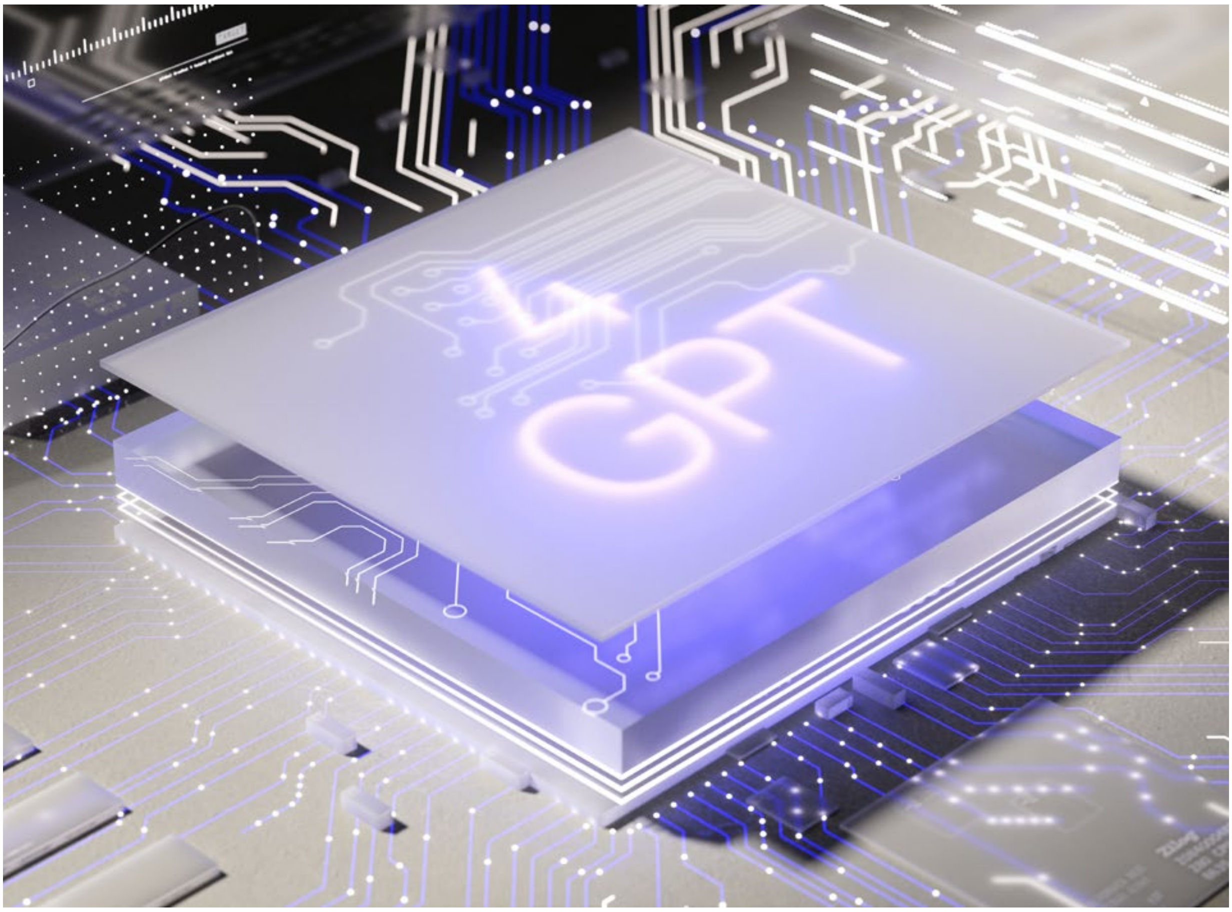

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Table 1
Emerging technologies, industries and businesses

No	Emerging industries and businesses
1	3D and 4D printing and additive manufacturing
2	3D printing
3	5G and faster, smarter networksd
4	Agriculture and food – precision agriculture, crop preservation, regenerative tech, alternative proteins
5	Artificial intelligence
6	Artificial intelligence and machine learning
7	Artificial intelligence and machine learning
8	Artificial intelligence
9	Autonomous vehicles
10	Batteries and energy storage – electric vehicle batteries, long-duration energy storage
11	Big data and augmented analytics
12	Bio revolution
13	Blockchains and distributed ledgers
14	Building technologies – geothermal heating, heat pumps, electric equipment
15	Carbon capture, utilization and storage (CCUS)
16	Carbon pricing (carbon tax and emissions trading schemes)
17	Carbon removal, capture and storage – point-source carbon capture, direct air capture
18	Circular economy – battery recycling, chemical cellulosic recycling, heat recovery, plastics recycling
19	Cloud and edge computing
20	Computer vision and facial recognition
21	Computing power
22	Crowd funding
23	Cybersecurity and cyber resilience
24	Datafication
25	Digital platforms
26	Digital trust
27	Digital twins
28	Digitally extended realities
29	Distributed infrastructure
30	Drones and unmanned aerial vehicles
31	Extended reality
32	From wearables to augmented humans
33	Future clean technologies
34	Future connectivity

No	Emerging industries and businesses
35	Future programme
36	Genomics and gene editing
37	Genomics
38	Hydrogen – electrolysers, fuel cells, methane pyrolysis
39	Hydrogen
40	Increased diversity
41	Industrial process innovation – electrification of heat sources, green steelmaking, green cement making
42	Information and communications technology
43	Intelligent spaces and smart places
44	Internet of Things
45	Internet of Things and the rise of smart devicesd
46	Machine co-creativity and augmented design
47	Mass personalization and micro-moments
48	Nanomaterials
49	Nanotechnology and materials science
50	Natural language processing
51	Nature-based solutions – monitoring and verification for forests, peatlands, mangroves
52	Next generation computing
53	Next-level process automation and virtualization
54	Quantum computing
55	Remote working, working from home and new flexibility
56	Renewables – solar, wind (onshore and offshore), grid innovation
57	Robotic process automation
58	Robots and business processes automation
59	Robots and cobots
60	Smarter devices
61	Social and environmental responsibility
62	Sustainable fuels – advanced biofuels, environmentally friendly fuels
63	The artificial intelligence revolution
64	Trust architecture
65	Voice interfaces and chatbots

Sources: Compiled by author on the basis of author's suggestions; Heid et al. (2022); Marr (2020); Marr (2022); McKinsey (2022).

2.3.1. Criteria for shortlisting emerging industry or business

The theory of change methodology makes it possible to explain how an emerging industry or business can lead to specific outcomes. This is achieved by drawing on a causal analysis of available evidence and the methods used for generating the evidence, on the basis that such evidence is the most appropriate for the state of the emerging industry or business. In order to better follow and appreciate the impacts associated with emerging industries and businesses, a number of important questions need to be answered that are generally consistent with the principles behind the theory of change and multiple-level perspective methodology.

On a life cycle basis, the questions that arise and which inform the perspective of this paper are:

- What are the expected impacts of the emerging industry or business?
- Are there any intermediate outcomes of the emerging industry or business?
- What does it take to facilitate the implementation of the emerging industry or business?
- What additional resources or inputs are needed for the change to happen?
- Are there possibilities for coupling to achieve combinatorial effects, and is the combined value delivered by multiple emerging technologies multiplicative across sectors?
- Will stakeholders be prepared to accept the change?

Guided by these questions, a set of criteria for shortlisting relevant industries and businesses was developed (see section 2.2.3.1), and an assessment of the impacts was carried out (see sections 3.2–3.5).

The overarching condition for selecting a given emerging industry and business is its proven ability to contribute to achieving sustainable development objectives. Specifically, the criteria were developed on the basis of the potential of the emerging industry or business to contribute to achieving national environmental, social and economic development imperatives that are aligned with global decarbonization efforts. This study used the following set of criteria:

1. Decarbonization potential (i.e. GHG emission reduction and sequestration potential, and contribution to the achievement of net zero and low-emission development pathways);
2. The potential for allied new businesses and industries springing from the parent technology (whether downstream or upstream);
3. Broad application across numerous sectors (i.e. applicability);
4. Ease of geographical application that consistent with diverse national/regional natural resource endowments;
5. Potential for replication;
6. Technological maturity;
7. Availability of methodologies and tools for assessing associated impacts;
8. Positive societal impacts;
9. The relative cost of the technology;
10. Ease of managing associated risks;
11. Potential for amplification through combinatorial effects (i.e. ease of combining or coupling multiple emerging industries and businesses to achieve multiplicative impacts);
12. Availability of knowledge, skills and literature.

2.3.2. Shortlisted emerging industries and businesses

Quantitative and qualitative approaches were used when shortlisting the emerging industries and businesses. This involved providing a ranking for each of the criteria listed in section 2.3.1 and using the fraction of the total score[6] (expressed as a percentage) as a shortlisting decision-making point. The full details of the scoring and shortlisting of the industries and businesses are provided in the Microsoft Excel file that accompanies this document. It is important to note that some of the 65 emerging industries and businesses listed in the spreadsheet are enablers that support the use and application of others and, although the enablers are critical in effecting the desired change, they are ranked low on the basis of the definitions provided above.

Table 2 shows the scores allocated to the three emerging industries selected for further analysis.

Table 2
Summary of scores for the three key emerging industries against each of the 12 criteria

Criteria for shortlisting emerging industries and businesses	**Scores of emerging industries and businesses**		
	Hydrogen	**CCUS**	**AI**
Decarbonization potential	High	High	Medium
Allied industries/businesses	High	Medium	High
Sector applicability	High	High	High
Geographical application	High	Medium	High/medium
Replication potential	High	High	High
Technology maturity	Medium/high	Medium/high	High/medium
Methods for impacts assessment	High	Medium	High
Societal impacts	High	High	High
Technology cost	Medium/high	Medium/high	Medium/high
Risk management	Medium	High	Medium
Application of combinatorial effect	High	Medium	High
Availability of knowledge, skills and literature	High	High	High
Total score	High	Medium to high	Medium to high

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[6] Fraction of total score is equal to the total score for an industry or business divided by 120. (Each criterion is ranked from 0 to 10, and therefore results in a highest possible score of 120 for the 12 criteria considered.)

Reaching net zero emissions by 2050 demands deep decarbonization worldwide, meaning all economies – big and small – will need to contribute towards this goal using available technologies, while considering how their national natural resources can contribute to the change required. Achieving the desired outcome, whereby all countries in all regions contribute to the global mitigation goal, leaving none behind, can be made possible by taking advantage of the versatility of hydrogen and CCUS.

CCUS is important for fossil fuel-dependent economies and industrial facilities where options for CO_2 abatement are very limited or completely impossible; while hydrogen technology provides the necessary flexibility in terms of mass production, facilitated by national natural resource endowments. The most advanced and matured technological pathways for hydrogen production are methane steam reforming, biomass gasification, and hydrolysis.

The tremendous potential that these two emerging industries provide can be further enhanced by using AI on a massive scale. In addition, the application of AI could significantly augment the efforts of governments, businesses and other stakeholders in abating GHG emissions and adapting to the impacts of climate change.

The three emerging industries and businesses (i.e. CCUS, hydrogen and AI) are discussed in chapter 3, where the impacts associated with their applications are reviewed and presented.

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3

SOCIAL, ECONOMIC AND ENVIRONMENTAL IMPACTS

Assessing the social, economic and environmental impacts of emerging industries and businesses is an important part of raising awareness and understanding among all stakeholders of their benefits or otherwise to society and towards achieving global climate change mitigation goals.

However, assessing the effectiveness of new and emerging industries and businesses is challenging because there are many uncertainties. In that context, identifying scientifically robust evidence of the likely impacts along the value chain is important information for all stakeholders, to inform change.

Similarly, an evidence-based approach contributes to developing standardized methods for assessing and reporting these impacts, with the view to avoiding the "shield of change[7]" and promoting their adoption, replication and scale up. The study that underpins this paper therefore focused on gathering, to the extent possible, information on impacts as reported in existing and publicly available technical reports and scientific journals. These impacts were then considered in some detail for the shortlisted emerging industries and businesses. Gathering such evidence could involve primary environmental and socioeconomic research.

This chapter presents the systematic and in-depth review and analysis of the social, economic and environmental impacts. It also describes the assessment methods and tools used.

3.1. Assessment methods

New policies and measures are needed if the world is to achieve the net-zero emissions target required to address climate change. However, enacting and implementing such new policies and measures brings an added requirement to identify and address their associated impacts. There are several methods and tools for assessing impacts arising from implementing policies and measures and, depending on the depth and complexity of the assessment study, several methods could be used either individually or in combination. The current study, however, focused on two main methods: the levelized cost of carbon abatement (LCCA) and life cycle assessment (LCA).

A report by Friedmann et al. (2020) explains how valuable insights and guidance for policy choices for a net-zero emissions world can be obtained using the LCCA method, and that method was applied when assessing the shortlisted industries and businesses identified in this study, conscious of the fact that other more robust numerical assessment methods could, in the future, complement this work.

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[7] Shield of change here means resistance to change.

LCA is widely recognized as a comprehensive tool for evaluating environmental impacts associated with products and processes. Environmental sustainability based on LCA remains one of the key requirements for selecting the processes involved in hydrogen production. This is because policymakers need to adopt transformative solutions based on robust data and evidence-based research to identify processes that go beyond a one-size-fits-all approach. The LCA methodology applied in the current study proved sufficient to provide the insights for creating the necessary awareness and understanding.

3.2. General observations on the impacts of the shortlisted emerging industries and businesses

A report by the global consultancy PwC highlighted the rapid increase in the climate technology market, which grew from USD 418 million globally in 2013 to USD 16.3 billion in 2019 in only seven years (PwC, 2020). Twelve months on, the 2021 report saw a further acceleration, with the average size of climate tech deals nearly quadrupling in the first half of 2021 and with over 200 per cent growth in terms of total volumes year on year (PwC, 2021).

There is overwhelming scientific evidence that the production and use of hydrogen coupled with CCUS can significantly accelerate the global pace of decarbonization to net zero emissions by 2050. Hydrogen could deliver many gigatonnes of abatement annually when used in various hard-to-abate industries, transport and stationary energy. The Hydrogen Council (2022) estimates that hydrogen demand could exceed 500 Mt by 2050, delivering up to 6 Gt of abatement.

Achieving that level of abatement requires an increasing demand and supply of green hydrogen at large scale (Fuel Cells and Hydrogen 2 Joint Undertaking, 2019). In this context hydrogen is a versatile, clean and flexible energy vector. It allows for large-scale integration of renewable energy sources because it enables energy providers to convert and store energy as renewable gas. Without hydrogen, the global deep decarbonization objective cannot be met.

CCUS is crucial to climate mitigation because these technologies can provide significant point source emission reductions in energy-intensive sectors. Significant deployment of CCUS is critical for lowering the costs of wider uptake of this technology. An analysis by the IEA in its *Energy Technology Perspectives Special Report 2020* (IEA, 2020) concluded that CCUS is one of the key technology areas for ensuring that energy systems around the world are put on a sustainable trajectory. Moreover, CCUS is the only group of technologies that directly contributes to both reducing emissions in key sectors and removing CO_2 to balance emissions that cannot be avoided. This is a critical part of reaching net zero targets and illustrates why reaching net zero will be virtually impossible without CCUS. In addition, CCUS is one of the two main ways of producing low-carbon hydrogen, which is crucial for future energy needs.

3.3. Impact assessment of carbon capture, utilization and storage

3.3.1. Scope and technology information

CCUS is a proven emission reduction solution, permanently removing CO_2 from the atmosphere. The benefits of CCUS are social, economic and environmental, with positive impacts at both the local and global level. In recent decades CCUS has often featured in lists of climate-smart technologies in high-profile government and corporate strategies. Without the deployment of CCUS at scale, the cost of meeting the long-term climate target would be prohibitively high. Moreover, without CCUS it may be impossible to achieve net zero in hard-to-abate heavy industries.

CCUS technologies encompass:

- Capture, which involves separating or purifying CO_2 from other gases produced during industrial activities, then compressing the CO_2;
- Transport, where the captured and compressed CO_2 is transported for storage or use;
- Utilization involves the creation of other products such as building materials and carbon fibre tubes;

- Storage involves the safe, secure and permanent storage of compressed CO_2 by injecting it into carefully selected subsurface geologic formations such as saline formations, depleted oil and gas reservoirs, and un-mineable coal seams, where it is trapped and permanently stored in porous rock (Hong, 2022).

Research and observable climate impacts point almost unequivocally to the need for a larger and faster climate mitigation effort to capture and permanently store CO_2 from large point sources and directly from the atmosphere through direct air capture technologies, but their deployment is still limited (Peridas and Mordick Schmidt, 2021). The latest flagship thought leadership report from the Global CCS Institute (Townsend et al., 2020) analyses the major benefits of large-scale investment and deployment of carbon capture and storage (CCS) and discusses the existing evidence related to the value of CCS under two overarching themes:

1. CCS is an essential technology for economically meeting long-term climate targets and for risk mitigation through:
    - Achieving deep decarbonization in the hard-to-abate industries;
    - Enabling the production of clean hydrogen at scale;
    - Providing low-carbon dispatchable power;
    - Delivering negative emissions;
2. CCS is a driver of economic growth and employment by:
    - Creating and sustaining jobs;
    - Supporting economic growth through new net-zero industries and innovation spillovers;
    - Facilitating a just transition by alleviating geographic and timing mismatches;
    - Enabling infrastructure reuse and deferral of decommissioning costs.

The versatility of CCS and its ability to reduce both the flow and stock of CO_2 makes it a strategic **risk management tool** for climate mitigation.

Limiting the availability of CCUS would considerably increase the cost and complexity of the energy transition by increasing reliance on technologies that are currently more expensive and at earlier stages of development.

The AR6 (IPCC, 2022) regards actively removing carbon from the atmosphere through CCUS as a key part of keeping global warming to within 1.5 and 2°C. The AR6 states that, alongside drastic cuts in emissions, “negative emissions” technologies are likely to be a necessary part of the transition to net zero because they capture CO_2 emitted from major sources including fossil fuel power plants and enable it to be used or safely stored.

The AR6 acknowledges the importance of a range of measures to address atmospheric carbon. These include:

- Compressing captured CO_2 and injecting it into the ground;
- Tree planting (reforestation and afforestation);
- Bioenergy with carbon capture and storage (known as BECCS) – an approach in which CO_2 is captured from flue gas when biomass such as sugarcane is used for generating renewable energy.

The AR6 also acknowledges a significant role for direct air capture, and the potential for methods that use nature-based solutions such as the oceans to capture and store more carbon than they do already.

CCUS is an essential complement to emission reduction efforts because it offsets unavoidable CO_2 emissions from the hardest-to-abate industries, which would otherwise make it impossible to reach net zero. For instance, the AR6 says that CCUS will be “essential for eliminating the limestone calcination process emissions” associated with making Portland cement in cement and concrete production.

The AR6 warns that without CCUS the world’s fleet of coal and gas plants would need to retire 23 and 17 years early, respectively, to keep emissions low enough to restrict global warming to between 1.5 and 2°C. It also warns that: “Practically all long-lived technologies and investments that cannot be adapted to low-carbon and net zero emission modes could face **stranding** under climate policy,” and suggests that carbon-intensive facilities could be adapted by pairing them with CCUS technologies to prevent them from becoming "**stranded assets**" prematurely, which would increase transition costs and reduce public acceptance.

3.3.2. Impact assessment methods for CCUS

According to the literature consulted for this report, a number of different methods have been used for assessing the decarbonization and socioeconomic potential for CCUS. The methods range from physical models to integrated quantitative models, including the following:

- **Proposed new carbon capture and storage baseline and monitoring methodology form** (CDM- CCS-NM-FORM) (Version 2.0) provides guidance on how to implement the technology in a safe and secure manner (UNFCCC, 2013);
- **Integrated assessment models (scenario models)** explore interactions between climate and socioeconomic systems and present pathway options for meeting climate goals;
- **Numerical simulation** such as the Carbon Capture Simulation Initiative (CCSI) Toolset is used for assessing the impact of CCUS on water and subsurface transport over multiple phases;
- **Life cycle assessment** has been used in several studies that assess the environmental impact of CCUS systems, including Rao and Rubin (2002), Viebahn et al. (2007) and Pehnt and Henkel (2009);
- **Economic impact assessment** using computable general equilibrium modelling, such as the EYGEM model (Alairys, 2018);
- **Qualitative assessment** of the potential social and environmental benefits (Alairys, 2018);
- **Dynamic Recursive Global Trade Analysis Project** model and the input–output method have been used for assessing the socioeconomic effects of CCUS (Chen and Jiang, 2022).

3.3.3. Life cycle assessment for CCUS

To better appreciate the role of CCUS technology in the global decarbonization effort, it is important to evaluate the social, economic and environmental benefits from the four stages of the CCUS technology (i.e. CO_2 capture, transport, utilization and storage).

Most of the significant social, economic and environmental impacts associated with CCUS happen at the capture stage where, the true value and benefits of CCUS arise. Figure 1 shows the system boundary applied for an LCA of CCUS technology. This is consistent with the IEA schematic of CCUS shown in figure 2.

Note that figure 1 is very simplistic: CO_2 captured may be transported, utilized or stored, and it is not linear and may not necessarily follow the sequence as portrayed. However, figure 1 allows for the discussion of impact categories within the four stages of the CCUS process.

Figure 1

Life cycle assessment system boundary for carbon capture, utilization and storage

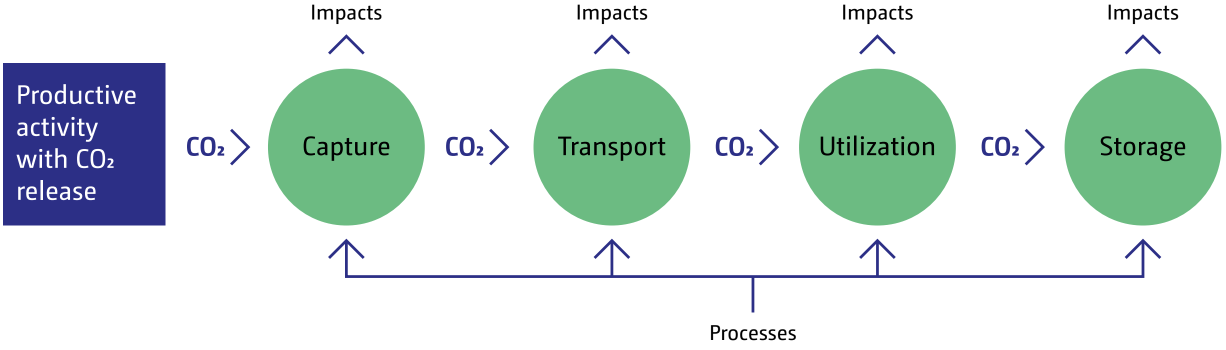
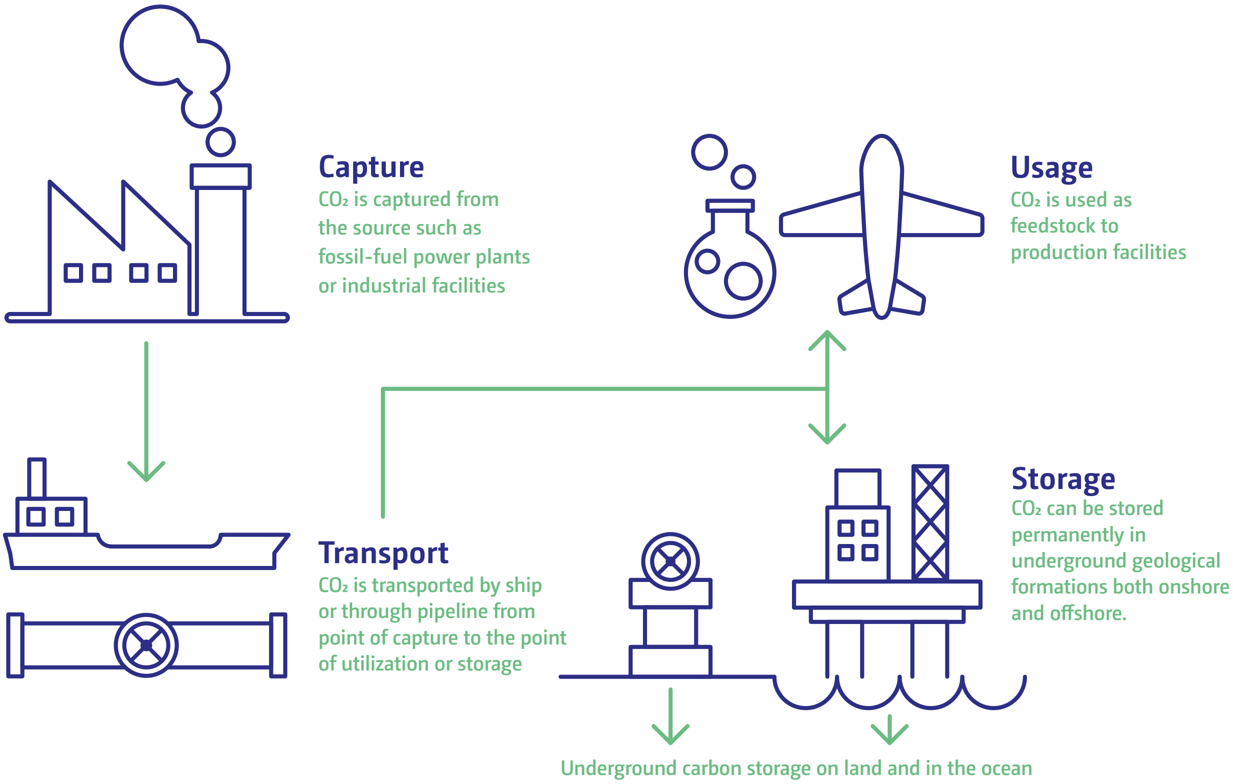


Figure 2
Schematic of carbon capture, utilization and storage



3.3.4. Societal impacts of CCUS

The adoption of CCUS technology could accelerate critical societal benefits during the construction and operational phases. The social impacts of deploying CCUS at scale include the following:

- **Creation and sustenance of jobs** – There are opportunities to create jobs in the construction, operation and maintenance of CCUS facilities. CCUS construction can create jobs for both low- and high-skilled workers at the peak of construction, but many of these jobs only endure for the construction phase. Conversely, operating CCUS facilities will require a relatively small number of skilled workers (managers, operators, maintenance personnel and lab technicians who normally work on shifts). These CCUS operation jobs are often long term, enduring throughout the life of a facility;

- **Indirect jobs in the supply chain** – The employment multiplier effects of CCUS deployment in industries can be large, but the indirect jobs are more geographically dispersed and are less likely to be additional (i.e. new);

- **Increase of skills and knowledge** – Integrated CCUS deployment could enhance skills and unlock innovation capacity among the industry players as a strategy for preventing economic and social disruption;

- **Stranded assets and workers** – The transition to a net-zero carbon economy will boost prosperity, but there will be winners and losers. One of the challenges of achieving a just transition is the disconnect between the geographic spread of job losses and gains, and the timing of these changes. If the transition is planned poorly, it could result in stranded assets and stranded workers and communities in those regions most at risk of job losses;

- **Stability** – Deployment of CCUS could provide employment opportunities at the time and place where they are most likely to be needed to support the just transition to a net-zero economy. CCUS could enable existing industries to continue to make a sustained contribution to local economies while transitioning to a net-zero economy;

- **Societal acceptance** – Societal acceptance of CCUS is based on the risk-benefit perception and information provision (Yang et al., 2016). There is a public perception of risk associated with CCUS owing to concerns about sequestration technology and potential leakage of CO_2 (L'Orange Seigo et al., 2014). Witte (2021) argues that in addition to the technical–economic, ecological and political aspects, the question of social acceptance is a decisive factor for the implementation of such low-carbon technologies.

3.3.5. Economic impacts of CCUS

The deployment of CCUS technology in multiple sectors could also generate economic benefits. including the following:

- **Boost clean economic growth** – The deployment of CCUS can stimulate substantial clean value-added growth through industry chain transmission and job creation (Chen & Jiang, 2022). Specifically, it can increase productivity in industries involved in the construction and operations phases of CCUS (Alairys, 2018; Townsend, 2020);

- **Substantial flow-on effects** – CCUS investment can also provide cascading economic benefits through agglomeration and clustering of allied industries. When CCUS investment is carefully infused into industry, it can boost productivity and efficiency from increased transactions and interactions between firms, as well as competition, innovation and knowledge creation. It could stimulate innovation as companies compete for market share, cascading into growth;

- **Source of high-value spillovers that can stimulate innovation-led growth** – CCUS technology is a higher value emerging business. The largest sources of innovation for CCUS deployment are AI, biotech and ICT;

- **Extension of the lifespan of existing infrastructure** – Use of CCUS can avoid stranded assets, because the lifespan of existing infrastructure can be extended, and the cost of decommissioning adjusted, by adopting CCUS. For instance, CCUS can provide opportunities for re-using existing oil and gas infrastructure by repurposing it for CO_2 transport and storage. This could provide material cost savings that benefit both operators and taxpayers. But there is a range of commercial, technical, operational and regulatory risks that could discourage the re-use of particular aspects of infrastructure. The rationale for re-using infrastructure ultimately rests on whether the cost savings of re-purposing assets outweigh the risks and costs of remedial work associated with using the older infrastructure.

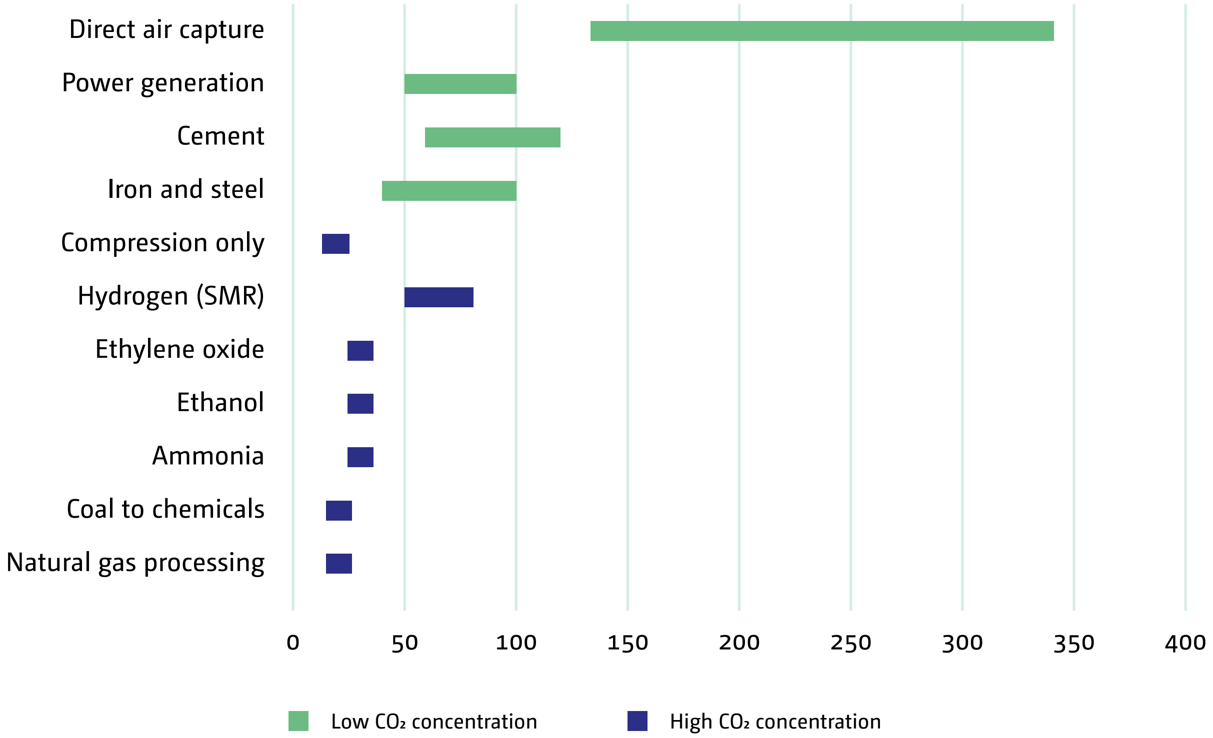
- **Economy-wide pathways to net zero emissions** – Greig and Uden (2021) explored the value that CCUS provides in time-bound, economy-wide transitions to net zero emissions by considering the value on three levels: (a) the threshold value (i.e. whether or not CCUS is necessary in economy-wide pathways to net zero); (b) the commercial value (i.e. the role of CCUS in minimum-cost pathways to net zero); and (c) the option value (i.e. whether or not the inclusion of CCUS in a mitigation portfolio reduces the risk of not meeting net zero, the given socio-technical uncertainties facing alternative pathways. They showed that CCUS also provides option value in a technology portfolio even when the planned pathway to net zero either does not include CCUS or includes only a limited amount of CCUS. The option value exists by providing a hedge against plausible (but hard to anticipate) real-world execution challenges for certain low-cost mitigation pathways, including those related to: capital mobilization; supply chains; siting and permitting; and potential public and political opposition owing to land-use impacts or disaffected industries.

However, there are some risks associated with deployment of CCUS that need to be taken into consideration, as follows:

- **Economic barriers exist to the adoption of CCUS** – The deployment of CCUS has the potential to increase the electricity cost in CCUS-fitted thermoelectric power systems (David and Herzog, 2000). Therefore, there is a need of large, long-term and sustainable funding source for achieving and scaling up the significant reduction in CO_2 emissions (Gibbins & Chalmers, 2008);
- **Wide range of abatement costs** – Baylin-Stern and Berghout (2021) noted that CCUS applications do not all have the same cost implications (see fig. 3). Looking specifically at carbon capture, in 2019 the costs varied greatly by CO_2 source, ranging from USD 15–25/t CO_2 for industrial processes producing "pure" or highly concentrated CO_2 streams (e.g. ethanol production or natural gas processing) to USD 40–120/t CO_2 for processes with "dilute" gas streams, such as cement production and power generation. Capturing CO_2 directly was the most expensive approach in 2019 but nonetheless could play a unique role in CO_2 removal.

Figure 3

Levelized cost of CO2 capture by sector and initial CO_2 concentration in 2019 USD/tonne



Reproduced from IEA 2019

3.3.6. Environmental impacts of CCUS

CCUS achieves mitigation via emission reductions, emission avoidance, and/or negative emissions.

Literature has documented both positive and negative environmental impacts of CCUS, ranging from potential air improvements to the risk of CO_2 leakage in groundwater and back into the atmosphere. The positive and negative environmental impacts of CCUS are summarized below.

Positive impacts of CCUS:

- CCUS can help avoid the CO_2 emissions at point sources that hitherto would have been emitted into the atmosphere;
- CCUS can decrease the stock of CO_2 emissions already in the atmosphere through CO_2 removal technologies. This could contribute to enabling a low-emissions future (Alairys, 2018);
- CCUS will improve air quality because it reduces air pollutants when used for hydrogen production or when fitted within a thermal plant that does not have a pollution control system.

Negative impacts of CCUS:

- CCUS deployment in a power plant could impose water stresses owing to the additional water requirements for chemical and physical processes to capture and separate CO_2 in CCUS-fitted fossil-fuel thermal plants (Eldardiry & Habib, 2018);
- The parasitic load imposed by CCUS in power plants can reduce their efficiency and result in a requirement for more water for cooling the plant during operation;
- Groundwater contamination due to CO_2 leakage from geological sequestration could affect water quality;
- Leakage of CO_2 via boreholes overlaying rocks or natural fractures and faults may be a local effect (IPCC, 2005);
- Large-scale hazards include global climate effect due to low-level CO_2 leaked back into the atmosphere through either accidental or deliberate release (Eldardiry & Habib, 2018).

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3.3.7. Cross-cutting issues and policy enablers of CCUS

In addition to the reported impacts, some published research has also highlighted the critical policy issues that could scale up the impacts of CCUS. For instance, Gibbins and Chalmers (2008), reported on the need for technical regulation for CO_2 transport and geological storage and need for strengthening policy support for CCUS to drive innovation and deployment, albeit that the CCUS technology is generally designed to avoid leakages.

3.4. Impact assessment of hydrogen production

LCA is the most appropriate method for assessing the impact of hydrogen production. However, a limitation of the LCA studies identified in the existing literature is that they often focus only on a subset of technologies and tend to overlook environmental impacts beyond the GHG emissions that contribute to climate change. In addition, attributional studies were more commonly found in the literature, whereas for the purposes of this paper the focus needs to be on consequential LCA studies. That being said, the studies reflected in this section have highlighted that “low environmental impacts” are not guaranteed, even for the renewable-based routes, when the full supply chain is evaluated.

In this context, the transition to long-term sustainable hydrogen generation systems should be underpinned by thorough assessments of the available technologies, taking into account the additional costs of the environmental impacts over the entire supply chain and point of generation. According to Al-Qahtani et al. (2021) so far no single publication has presented a comprehensive assessment of the most promising hydrogen production technologies, considering their cost and externalities due to impacts on human health, ecosystem quality and resources depletion. The work of Al-Qahtani et al., however, addresses some of those shortcomings.

3.4.1. Scope and technology information

Hydrogen is a clean energy carrier and a primary energy source, and it can be used as a fuel in transportation, electricity production and as a feedstock in industry. As such, hydrogen offers a range of benefits for simultaneously decarbonizing the transport, residential, commercial and industrial sectors. However, the definition of hydrogen as a zero-carbon fuel depends on how it is sourced. For example, when used as an energy carrier for electricity supply, hydrogen may be produced using either renewable energy sources or hydrocarbons such as natural gas or coal.

There are three main hydrogen production pathways, categorized as follows (Brandon & Kurban, 2017):

- **Power-to-gas (P2G)** – Electricity is used to generate hydrogen via polymer electrolyte membrane electrolysis technology. The hydrogen is then either injected into the gas distribution grid or transformed to synthetic methane (i.e. methanation);

- **Power-to-power (P2P)** – Electricity is used to generate hydrogen via electrolysis. The hydrogen is then stored in a pressurized tank or an underground cavern or re-electrified when needed using a fuel cell or a hydrogen gas turbine. The hydrogen produced can also be used in fuel cells for electric vehicles in the transport sector, which is referred to as a **power-to-fuel (P2F)** process;

- **Gas-to-gas (G2G) –** The SMR process is used for producing hydrogen from natural gas, and around 95 per cent of global hydrogen production uses SMR technology. However, that process generates CO_2, so CCUS technology is needed to capture the CO_2 released during the process.

Other production pathways exist. For example, hydrogen can be produced through thermochemical, electrolytic, photolytic or biological processes, as follows:

- Thermochemical processes use heat and chemical reactions to release hydrogen from water or from organic materials such as fossil fuels and biomass. Some thermal processes use the energy in various resources (e.g. natural gas, coal or biomass) to release hydrogen from the material’s molecular structure. Thermochemical processes include natural gas reforming (i.e. SMR) biomass gasification, biomass-derived liquid reforming, and solar thermochemical hydrogen production;

- Electrolytic processes use electrolysers and electricity to split water into hydrogen and oxygen;
- Photolytic processes use light energy to split water into hydrogen and oxygen through either photoelectrochemical or photobiological processes;
- Biological processes use microbes such as bacteria and microalgae to produce hydrogen through biological reactions, using sunlight or organic matter (microbial biomass conversion) or through photobiological processes.

The optimum hydrogen pathway depends on a trade-off between several factors, including system costs, efficiency, decarbonization impact and the practical feasibility (e.g. public acceptance) of changing the existing energy system in a given area to incorporate these new technologies. Figure 4 illustrates the prominent hydrogen production and utilization routes, while table 3 summarizes the various levels of technological maturity and social, economic and environmental impacts of these production pathways.

Figure 4
Schematic of hydrogen production and utilization

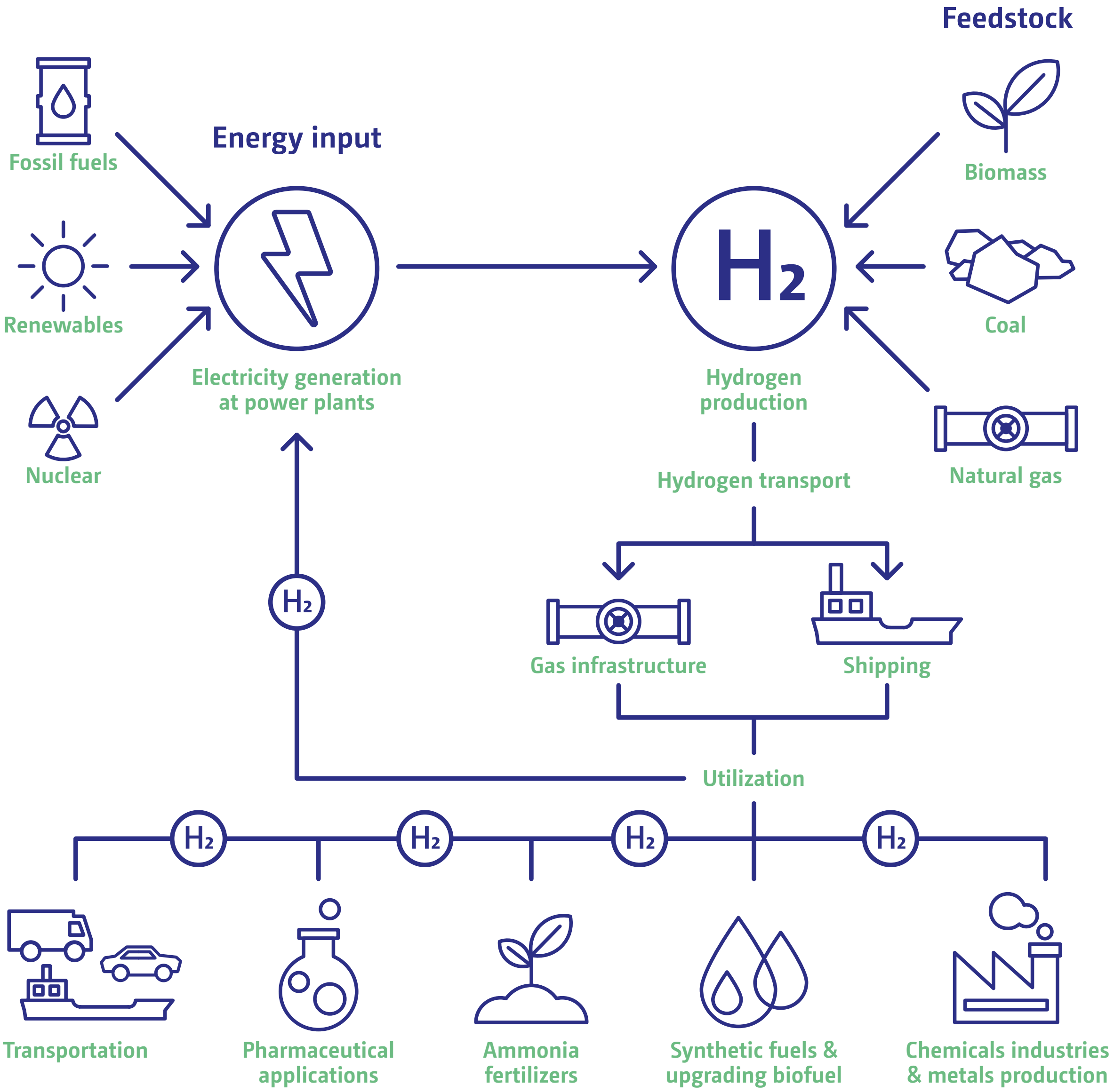


Table 3
Hydrogen technology readiness levels

Technology name	Technology readiness level
Biomass gasification	5-6
Biomass gasification with CCS	3-5
Coal gasification	9
Coal gasification with CCS	6–7
Electrolysis from wind energy	9
Electrolysis from solar PV energy	9
Electrolysis from nuclear energy	9
Methane pyrolysis	3-5
Steam methane reforming	9
Steam methane reforming with CCS	7-9

Source: Thomas H, Armstrong F, Brandon N, David B, Barron A, Durrant J, et al. Options for producing low-carbon hydrogen at scale; 2018
Note: “Technology readiness” score ranges from 1 (not yet practical) to 9 (already operational).

Despite the technology readiness levels shown in table 3, biomass gasification is considered one of the most feasible, sustainable and potentially carbon-neutral ways to generate hydrogen (Saidi & Omri, 2020). Since biomass is a renewable feedstock that absorbs atmospheric CO_2 during growth, it has a much lower net CO_2 footprint than fossil-based fuels. However, the economic feasibility of hydrogen output from biomass must be closely related to the availability and affordability of raw materials in the local area. The main attributes of the supply materials are the biomass physicochemical properties, distribution and hydrogen rate. Biomass feedstocks vary widely in structural composition and shape, so all these characteristics must be considered when combining the feedstock with the appropriate conversion technology (Osman et al., 2021).

Hydrogen is popular because of its high energy content, environmental compatibility and ease of storage and distribution, and there has been an unprecedented increase in hydrogen technologies, infrastructure and applications. Hydrogen is one of the keys to the energy transition (Hydrogen Council, 2021) and sector-coupled energy systems. It has the potential to cut emissions from heavy industry and transport. For instance, in the transport sector, hydrogen is expected to replace liquid and gaseous fuels by 2100. However, its deployment must be economically viable and socially acceptable to maximize the decarbonization impact and minimize its resource requirements.

The decision to promote hydrogen over other energy systems arises from the following facts: (a) it is the only option for at-scale decarbonization of certain segments in the transport, industry and building sectors; (b) it plays a systemic role in the transition to renewable energy sources by providing a mechanism to flexibly transfer energy across sectors, time and place; and (c) the transition to hydrogen is aligned with customer preferences and convenience. The latter is key, because low-carbon alternatives that do not meet customer preferences will likely face adoption difficulties.

Hydrogen provides both a mechanism for sector coupling and the option to store energy at large scale over long periods of time or transport it from regions of supply to centres of demand. In transitioning to the hydrogen economy, however, cost-effective production methods, policies, regulatory frameworks (including codes and standards), research and development, and (above all) hydrogen infrastructure development are areas that need to be investigated in detail to inform investment decision-making.

Hydrogen purification and compression (subsystems) are additional issues that need to be considered alongside the LCA when selecting the production method for hydrogen (Dawood et al., 2020). Given its suitability across a range of energy applications and carbon neutrality at the point of use, hydrogen is regarded as a "green" energy vector that offers a unique cross-system opportunity for fundamental change in the energy landscape.

Despite its versatility, some of the physical and chemical properties of hydrogen come with a high level of risk that needs to be considered in the early stages of the transition.

Hydrogen is an odourless, colourless and flammable gas. These properties give rise to safety concerns, especially because if a leak is not detected and gas collects in a confined area it can ultimately ignite and causes explosions. Furthermore, hydrogen-driven embrittlement of metals could damage pipelines and containers owing to hydrogen's small molecular size; thus, it escapes through materials.

Like electricity, hydrogen is an energy carrier and not an energy source. Using hydrogen to store renewable energy instead of that energy being wasted is hydrogen's key benefit: it is storable, usable and transportable (Abe et al., 2019). At the same time, the low temperature required for liquefied hydrogen storage at ambient pressure and a temperature (−253 °C) raises quite a few risks. If liquefied hydrogen comes into contact with the skin it can cause cold burns; furthermore, leakage can result in a combination of liquefied air and hydrogen, resulting in an explosive mixture or the formation of flammable or explosive conduits (Atilhan et al., 2021).

The methods and source materials used for producing hydrogen have an impact on how environmentally clean it is, which is usually described by a colour coding system, illustrated in figure 5, and summarized as follows:

- **Grey hydrogen** is produced using fossil fuels such as natural gas. A tonne of hydrogen produced in this way is responsible for 10 t CO_2 (Dvoynikov et al., 2021)

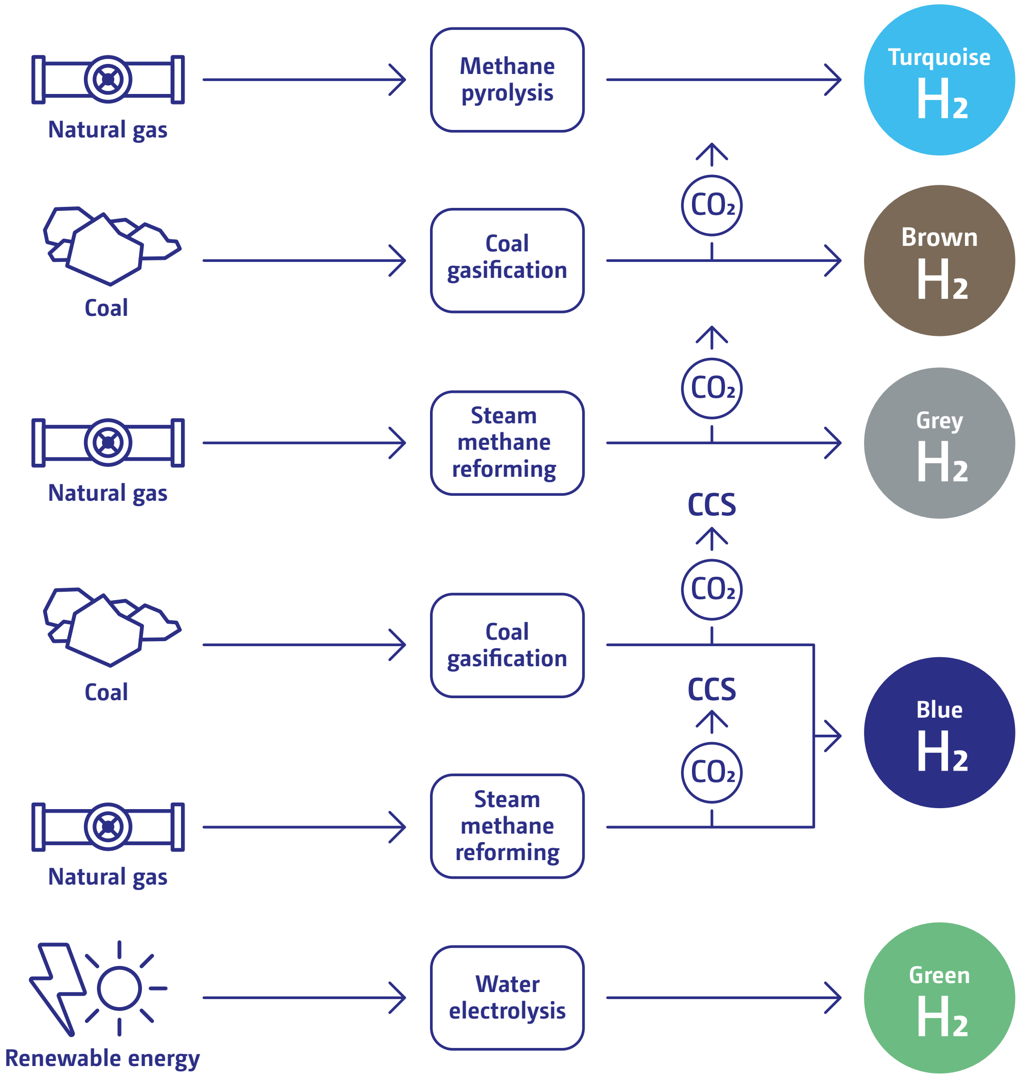
- **Blue hydrogen** is produced using fossil fuels, as for grey hydrogen, but with the addition of carbon capture and storage to mitigate emissions;

- **Green hydrogen** is typically produced using 100 per cent renewable sources such as wind or solar energies with a lower carbon footprint;

- **Brown hydrogen** is produced via the gasification of coal-based fuel;

- **Turquoise hydrogen** is produced from the thermal decomposition of natural gas; that is, methane pyrolysis or cracking by spitting methane into hydrogen and carbon at a temperature ranging from 600 to 1200–1400°C (Dvoynikov et al., 2021). This process produces black carbon (soot) as a by-product instead of the CO_2 emissions produced in grey hydrogen generation, allowing for the sequestration of carbon emissions in the form of solid carbon. However, the stability of the carbon in this black soot is critical for long-term carbon sequestration as is utilizing renewable energy sources in the high-temperature process to achieve carbon neutrality. Interestingly, biogas pyrolysis could produce hydrogen with a negative carbon footprint.

Figure 5
Color classification of hydrogen and the production process



3.4.2. Impact assessment methods of for hydrogen production

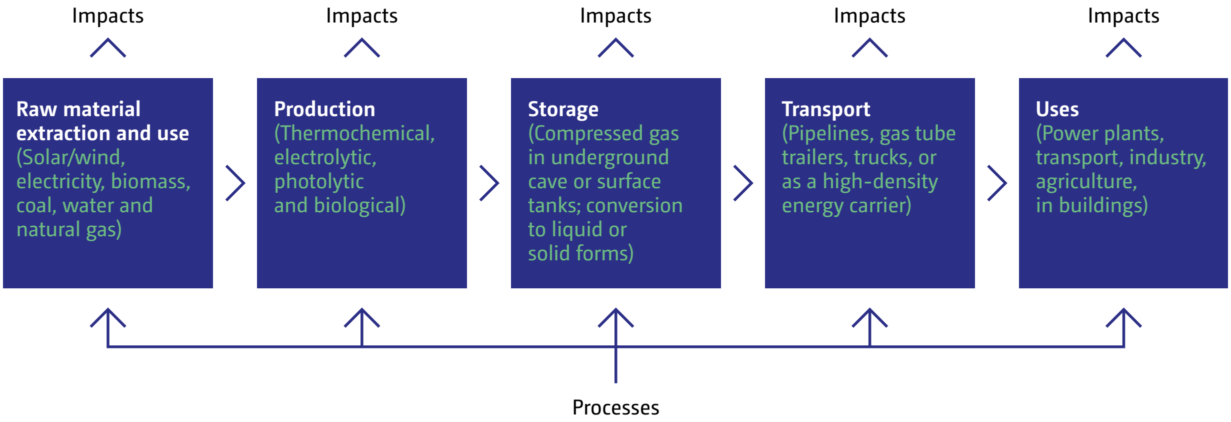
According to the literature consulted for this report, LCA and the integrated process model are the main methods for assessing the impacts of hydrogen deployment (Ullman & Kittner, 2022). The LCA system boundary encompasses the raw material acquisition, production, storage, transportation and use process stages, as shown in Figure 6, so the impacts associated with hydrogen, as a new and emerging business/industry, depend on the pathways within these five process stages.

The impacts are further exacerbated by the choice of the production system, namely distributed or centralized: distributed generation avoids many of the substantial infrastructure barriers faced by centralized generation, and thus has fewer social, economic, safety, security and environmental concerns; while centralized generation has broader and far-reaching impacts regarding raw materials acquisition and technological choices for production, storage, transportation and use.

Figure 6 suggests a “whole system thinking approach” for hydrogen as a new business. This approach makes it possible to consider the true cost of production by looking at the wide range of technologies coupled with an LCA that considers economic evaluation and environmental externalities. Al-Qahtani et al. (2021) used this approach to estimate the “real” total cost of hydrogen by transparently ranking the alternative hydrogen technologies based on monetized values of environmental impacts on human health, ecosystem quality, raw material, or resource use, in addition to a levelized cost of hydrogen production.

Life cycle assessment is recognized as a comprehensive tool for evaluating environmental impacts associated with products and processes (Sevigné-Itoiz et al., 2021), but it is also one of the key requirements when selecting processes for hydrogen production (Department for Business, Energy & Industrial Stategy, 2021) .This is because policymakers need to adopt transformative solutions based on robust data and evidence-based research to identify processes that go beyond a one-size-fits-all approach.

Figure 6
Life cycle assessment system boundary for hydrogen



3.4.3. Societal impacts of hydrogen production

- The production and use of hydrogen will lead to **transformational changes in the structure of societies** as they transition into new communities powered by cleaner fuels;
- New societies and communities that use hydrogen-powered cars, buses, stoves and other residential and commercial heating technologies will emerge, **changing mindsets and perceptions** about the use of hydrogen-powered equipment;
- Using cleaner fuels has the added benefit of improving air quality and the population’s general health. Hydrogen represents a good choice of energy carrier because it is a versatile, clean and flexible energy vector;
- Hydrogen production brings with it the potential for **creating good-quality and sustainable jobs** in allied upstream and downstream new businesses and industries;
- It can also **lead to capacity and knowledge enhancement** because of reskilling and retooling of existing jobs;
- Hydrogen has a **high potential for reducing inequality among nations** as countries become more and more energy independent;
- Hydrogen production systems favour more decentralized production and use, helping to **address gender inequalities and empowerment**, especially in communities where energy systems are largely centralized;
- It can also **promote intergenerational equity**, including through improvement in the quality of ecosystems.

3.4.4. Economic impacts of hydrogen production

- **Integration with low-carbon alternatives in energy, transport and industry –** Hydrogen can be linked with other low-carbon alternatives to enable a more cost-effective transition to decarbonized and cleaner energy systems (Brandon & Kurban, 2017). It can boost the opportunity to use renewables in transport and hard-to-abate industries. An integrated hydrogen and energy system can ensure supply (storage and transport energy), affordability (hydrogen is abundant and increasingly competitive) and sustainability (low life cycle carbon emissions). Electricity and hydrogen in mobility applications can boost companies in various industries, such as logistics suppliers, transportation companies, garages, agricultural contractors, ship builders, automobile leasing companies, sail boats and city distribution.

- **Promotion of industries and revitalization of regional economies through patents relating to hydrogen technology –** Developing hydrogen technology can result in an increase in research and development. Countries such as Japan are far advanced in this area, and this will result in more patents, which positively correlates with increasing revenues.

- **Reschedule the decommissioning of existing gas infrastructure –** Existing gas infrastructure can be used to transport renewable energy in the form of hydrogen. The investment needed to support the adoption of hydrogen could be reduced because existing gas infrastructure can be modified for this purpose.

- **Use of existing infrastructure –** Industries can use hydrogen that can be transported through existing pipelines.

- **Enable large-scale, efficient renewable electricity integration to compensate for the intermittent character of solar and wind** – The advent of hydrogen takes away the inefficiencies associated with the challenges of intermittent solar and wind because hydrogen can be used in combination with those technologies to support electricity production.

- **Decarbonization for industrial energy use –** Industries would be able to use a mix of green electricity and green hydrogen to produce high-temperature steam, which is necessary for many industrial processes and the growth of economies.

- **Serving as a feedstock for industry –** Carbon from biomass and green hydrogen could be the main feedstock for the production of every bulk chemical product. Enclaves with an integrated chain of companies can use and process one another's products and services.

- **Stimulation of new businesses –** The technical and economic success of hydrogen-based distributed energy systems will stimulate new business ventures. Hydrogen power parks will provide an economic development path for the integrated production of energy services such as electricity, transportation fuels, and heating and cooling.

The success of a transformation to hydrogen is not just that it could reduce carbon emissions but that it could also boost **global industrial competitiveness, reduce resource dependency, cut energy costs, and improve citizens' lives** as air quality improves.

In addition, developing a hydrogen economy will boost national economies (i.e. GDP) by stimulating **allied upstream and downstream industries and businesses**. For example, the production of green ammonia for fertilizer production could revolutionize the agricultural sector, allowing many agro-based developing nations to leapfrog development, just as the development of cost-effective and durable fuel cell vehicles could prove attractive to manufacturers, marketers and consumers by replacing mechanical or hydraulic subsystems with electrical energy delivered by wire, potentially improving efficiency and opening up the design envelope; reducing manufacturing costs as manufacturers can use fewer vehicle platforms; and enabling the vehicle to offer mobile, high-power electricity, which could provide accessories and on-vehicle services more effectively than could alternatives (Committee on Alternatives and Strategies for Future Hydrogen Production Use, 2004). Indeed, a national energy system envisioned to rely on hydrogen as the commercial fuel could

deliver a substantial fraction of the nation's energy-based goods and services (Committee on Alternatives and Strategies for Future Hydrogen Production Use, 2004).

However, materializing the clearly impressive benefits of hydrogen deployment will require substantial but achievable investment. Financing the required infrastructure is also a consideration. It is estimated that building the hydrogen economy would require annual investments of USD 20–25 billion, or a total of about USD 280 billion a year until 2030 (Hydrogen Council, 2017).

Currently, renewable energy-based processes cannot produce hydrogen at a price or scale that is competitive with fossil fuels (IRENA, 2019; Parkinson et al., 2019, 2022). A major hindrance to the economic production of renewable-based hydrogen is the **substantial capital expenditure (CAPEX) required** (Padro & Putsche, 2010; Ruth, 2011). Therefore, effective policies will be needed to facilitate the transition to low-carbon economies. On the other hand, **facilitating and stimulating global economic growth** by investing in the hydrogen economy would make the transition to net zero less burdensome.

In short, since the resource base for the generation of hydrogen is wide-ranging, and the transition would **promote energy independence and national energy security**, ambitious and progressive governments could harness and develop their locally based energy systems, leading to inclusiveness leaving no nation or region behind.

3.4.5. Environmental impacts of hydrogen production

Hydrogen is a viable long-term option for reducing CO_2 emissions and a huge opportunity for reaching the Paris Agreement goal. Energy systems that rely on hydrogen have the potential to propel the early achievement of national long-term GHG emission reduction goals and can ramp up efforts to achieve net zero targets pledged by governments and corporations in the wake of calls for climate action. The positive and negative environmental impacts of hydrogen are summarized below.

Positive impacts of hydrogen:

- Hydrogen can largely reduce environmental stress or burden because no CO_2 is emitted when hydrogen is used to produce energy;
- Pollution in urban cities can be attributed to fossil fuels used in cars, buses and trucks for hauling goods. The use of hydrogen will reduce pollution levels in cities and urban centres, which have become a key concern for many governments and local authorities;
- If large quantities of hydrogen can be produced at competitive costs and without undue carbon release, hydrogen would offer marked advantages in the competition with other secondary fuels. First, hydrogen is likely to burn more cleanly in combustion engines. Second, hydrogen is better matched to fuel cell use than competing fuels; fuel cells could become the disruptive technology that will transform the energy system and enable hydrogen to displace petroleum and carbon-releasing fuel cycles.

Negative impacts of hydrogen:

- Hydrogen warming: the climate consequences of using hydrogen compared with fossil fuels strongly depends on time horizon and leakage rates (Ocko & Hamburg, 2022);
- Externalities associated with hydrogen production (e.g. loss of energy during the conversion of hydrogen, production of hydrogen using bioenergy, and negative impacts due to parasitic load in hydrogen production), if not carefully addressed, would decelerate technology implementation.

3.4.6. Cross-cutting issues and policy enablers for hydrogen production

Countries will need a clear and credible road map for hydrogen production, transportation, storage and utilization in order to achieve long-term and sustainable deep decarbonization based on a hydrogen economy. These road maps must be underpinned by substantial but achievable investment, driven principally by the private sector. The climate community and governments can play a crucial role in creating the necessary enabling environment by working together, as follows:

- Ensuring that mega funds which have been ring-fenced for climate technologies, such as Brookfield's USD 7 billion Global Transition Fund and TPG's USD 5.4 billion Rise Climate Fund, are accessible to developing countries to support hydrogen economy programmes;
- Collaboration on adopting a uniform methodology for calculating life cycle GHG emissions for hydrogen, developing comprehensive and science-based terminology, as well as standards or best practices for its deployment;
- Expanding collaboration on sustainable hydrogen production across all regions. This calls for the development of a sustainable hydrogen market by developing market stimulation programmes;
- Developing relevant codes and standards to promote widespread adoption of the hydrogen economy;
- Putting in place the necessary systemic, legal and regulatory frameworks;
- Developing bespoke institutional capacity-building and training packages to support the transition to the hydrogen economy;
- Establishing state ministries to support transition to a hydrogen economy, such as infrastructure development and service delivery mechanisms;
- Undertaking scientific assessments to pin down the national resource endowment potential for sustainable hydrogen production;
- Promoting decentralized production and use of hydrogen in the energy, industry and transport sectors, with the view to achieving net zero emissions growth;
- Developing systems for sustainable and transformational impacts monitoring, reporting and verification consistent with the enhanced transparency framework under the Paris Agreement;
- Supporting research and development and knowledge management infrastructure to promote peer-to-peer learning;
- Undertaking economic and financial analyses, including assessment of diversification of investments and business models for investment in the hydrogen economy;
- Promoting partnerships involving relevant national and international stakeholders from the public and the private sectors, as well as from civil society and the research and academic communities.

Another aspect of an enabling environment would be the development of a tradable guarantee of origin[8] for hydrogen (GOH) to decouple physical from commercial flows and thereby accelerate hydrogen deployment worldwide. The transaction of GOHs would be considered as purchasing renewable/low-carbon/decarbonized hydrogen even if the closest producer is not GOH-certified. However, GOH should not be treated as a stand-alone instrument, used to record and track different batches of hydrogen produced from various sources or technologies (i.e. green, blue, or brown hydrogen). Rather, to harness its full potential, a GOH should be a part of a comprehensive portfolio of guarantees of origin developed for all types of energy carrier reflecting the LCA used for calculating the carbon footprint of each type.

The GOH scheme would enable cross-border trade in sustainable hydrogen regardless of geographical location. In addition, if made into a binding regulation, GOH certification will be among

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[8] A guarantee of origin is an energy certificate defined in article 15 of the European Union on the promotion of the use of energy from renewable sources (directive 2009/28/EC). Guarantees of origin are used for showing to a final customer that a given share or quantity of energy was produced from renewable sources. See the first European Guarantee of origin for green and low carbon hydrogen under the CertifHy (https://www.waterstofnet.eu/_asset/_public/CertifHy/CertifHy_Leaflet_final-compressed.pdf)

the determining factors for the size of a carbon border mechanism and similar environmental levy, assuming that the scheme is based on a harmonized international framework (i.e. agreed basic definitions, verification procedures, etc.) However, it is important to note that the GOH certification should not be another barrier for countries, especially developing countries, as has been the case of impacts arising from implementing some climate change policies and actions (response measures).

3.5. Impact assessment of artificial intelligence

3.5.1. Scope and technology information

The fourth industrial revolution, which began at the turn of this century, marks the state of human development where computing power augments human production. It is characterized by a much more ubiquitous mobile internet, AI and machine learning. In this revolution, emerging technologies and broad-based innovation are diffusing much faster and more widely than in previous industrial revolutions. In *The Fourth Industrial Revolution*, Klaus Schwab, Founder of the World Economic Forum, suggests there is a need to rethink global economic, social and political systems to respond to the fourth industrial revolution because of the low level of leadership and understanding of the changes under way across all sectors (Schwab, 2016). In addition, the world lacks a consistent, positive and common narrative that outlines the opportunities and challenges of this revolution.

Climate change, in itself, is a disruptive system that is affecting all sectors of the global economy, irrespective of geography and capacity. The solution to the problem of climate change requires system thinking and the use of cognitive science, which can be provided in part by AI (Rolnick et al., 2022). As an academic subject, the field of study of AI describes the capability of machines to learn just like humans and their ability to respond to certain behaviours: but the application of AI goes further still. It attempts not just to understand but also to build intelligent entities. Thus AI refers to a set of techniques to approximate some aspect of human or animal cognition using machines (Calo, 2017).

AI seems particularly suitable for addressing climate change questions, an area rife with massive data challenges. Monitoring sources and emissions of GHGs has been happening for decades, but the data remain difficult to parse, analyse and use productively (Maher et al., 2022). AI could help to predict where carbon emissions will come from, which can help policymakers and financiers on decisions about how and where to regulate and invest in energy production, for example.

AI has been called the “new electricity”, given its potential to transform entire industries (Stanford Graduate School of Business, 2017). It offers reliability, and cost-effectiveness, solves complicated problems and makes decisions; in addition, AI restricts data from getting lost. AI is applied nowadays in most fields, including business and engineering. One of the most significant tools used by AI is “reinforcement learning”, which is based on testing success and failure in real life to increase the reliability of applications.

The nature of climate-relevant data poses challenges and opportunities. The use of technologies and intelligent system design has the potential to restore and regenerate the natural environment. According to Toews (2021) AI is: “a general-purpose technology with infinite potential use cases. There is perhaps no AI application that matters more for humanity than decarbonizing the atmosphere and slowing climate change. The opportunity for economic and societal value creation is virtually unbounded. It is hard to imagine a more worthy field for AI entrepreneurs, researchers and operators to devote themselves to in the decades ahead.”

AI is also an enabler of new and emerging industries or businesses at scale. Ye (2021) describes digitalization as the application of digital technologies (e.g. sensors, networked devices, cloud data storage, analytics) to physical equipment and systems to reduce energy use and carbon emissions across the economy, including in the power, transportation, buildings, industry and agriculture sectors.

One of the most obvious applications of AI to climate change is its potential to improve climate modelling and predictions. Beyond AI’s capabilities for climate science, it can also play an important role in efforts to reduce emissions across one of the largest contributors of GHGs: the electrical power sector, which comprises generation, transmission, distribution and electricity consumption. The sector has plenty of opportunities for AI, including accelerating the development of clean energy technologies, improving electricity demand forecasts, strengthening system optimization and management, and enhancing system monitoring.

Other opportunities include smart grids, smart meters and blockchains that could enable new businesses. Machine learning can be deployed to reduce emissions from today's standby generators and enable the transition to carbon-free systems by helping to improve necessary technologies (namely forecasting, scheduling and control) and helping to create advanced electricity markets that accommodate variable electricity and flexible demand (Rolnick et al., 2022).

AI can also be useful in helping to improve electric vehicle charge scheduling, congestion management, vehicle-to-grid algorithms, and battery energy management, as well as by assisting in the research and development of batteries for electric vehicles.

Finally, AI can help make the grid safer, more efficient and more reliable by integrating data from hazards such as wildfires and extreme storms, and adjusting grid operations accordingly (Victor, 2019).

It is important to note that AI can be part of the solution in any application, or a combination thereof, for policies and measures that aim to address climate change. As such, it is a tool that enables other tools and abatement methods to function optimally across all fields. It is therefore difficult to consider a single impact assessment methodology (such as LAC) as being applicable to AI. However, general impacts covered in existing literature have been summarized below.

3.5.2. Economic impacts of artificial intelligence and related digital technologies

Generally, digitalization and AI can deliver a wide range of economic benefits through employment creation, improved quality of life and enabling the adoption of green technologies. Digitalization and AI can also contribute to economic growth and the reduction of GHG emissions. For example, in the energy sector, the application of AI/digital technologies has the versatility to improve wind and solar generation forecasts and help to maximize the efficiency of the grid.

3.5.3. Societal impacts of artificial intelligence and related digital technologies

It has been estimated that AI and related digital technologies could deliver "e-health" services to 1.6 billion people across the developing and developed world; and that smart agriculture will boost yields by 30 per cent, avoid 20 per cent of food waste and could deliver economic benefits worth USD 1.9 trillion. At the same time, smart agriculture could reduce water needs by 250 trillion litres and abate 2.0 Gt CO_2 eq (GeSI, 2015).

3.5.4. Environmental impacts of artificial intelligence and related digital technologies

AI and digital technologies have the capacity to increase carbon abatement by 20 per cent (Inderwildi et al. 2020). AI technologies are likely to be more effective and could raise carbon abatement to 30 per cent. Real-time traffic information, smart logistics, intelligent lighting and other ICT-enabled solutions could abate 3.6 Gt CO_2 eq, including abatement from avoided travel (GeSI, 2015); and smart manufacturing, including virtual manufacturing, customer-centric production, circular supply chains and smart services, could abate 2.7 Gt CO_2 eq.

3.5.5. Cross-cutting issues and policy enablers of artificial intelligence and digital technologies

If AI is to be embraced as part of the climate strategy, it will be important to be aware of the trade-offs associated with these technological tools. As with all emerging technologies, AI may face uncertainity, high upfront costs and scrutiny by regulators. Stein (2020) analysed some of the major trade-offs associated with the increased use of AI to address electricity-related climate issues, including environmental impacts (Pearce, 2018), data privacy (Altman et al., 2018), investment and procurement, and accountability, safety and certification (Cheatham et al., 2019). Addressing these four trade-offs will require government intervention and the cooperation of numerous stakeholders.

Despite all its potential to reduce energy consumption (electricity usage) and optimize efficiencies associated with the electric grid, AI can be a large consumer of electricity. Data centres are estimated to consume more than 2 per cent of the world's electricity (Pearce, 2018) and these environmental impacts through disclosure requirements (Lacoste et al., 2019), certification regulations (Sokol & Comerford, 2016) and increasing data sharing (Stein, 2020). To address the data privacy trade-off, which is a key concern for all applications of AI, Stein (2020) proposes that stakeholders and regulators take several important steps to minimize the negative privacy implications of using all this energy data by considering avenues to facilitate collaboration among stakeholders by putting in place (a) rigorous procedures for anonymizing energy data; and (b) regulating data ownership.

A key policy tool for facilitating the use of more AI for climate issues is funding. If AI has the potential to serve as a cost-effective diagnostic tool for the electricity industry to reduce GHGs, why have utility businesses not jumped on board? One answer may lie in the difficulties of obtaining cost recovery for emerging technologies. For example, in the United States, decisions about cost recovery for utility investments, including emerging technologies, are made by state public utility commissions. Given how many utilities need to obtain regulatory approvals of their expenditures to obtain cost recovery, the regulatory treatment of emerging technologies is a critical factor in the advancement of AI to enhance efficiencies across the electricity sector. There is a general need to consider and address issues related to public investment, non-utility private investment and utility investment in AI (Monast & Adair, 2014).

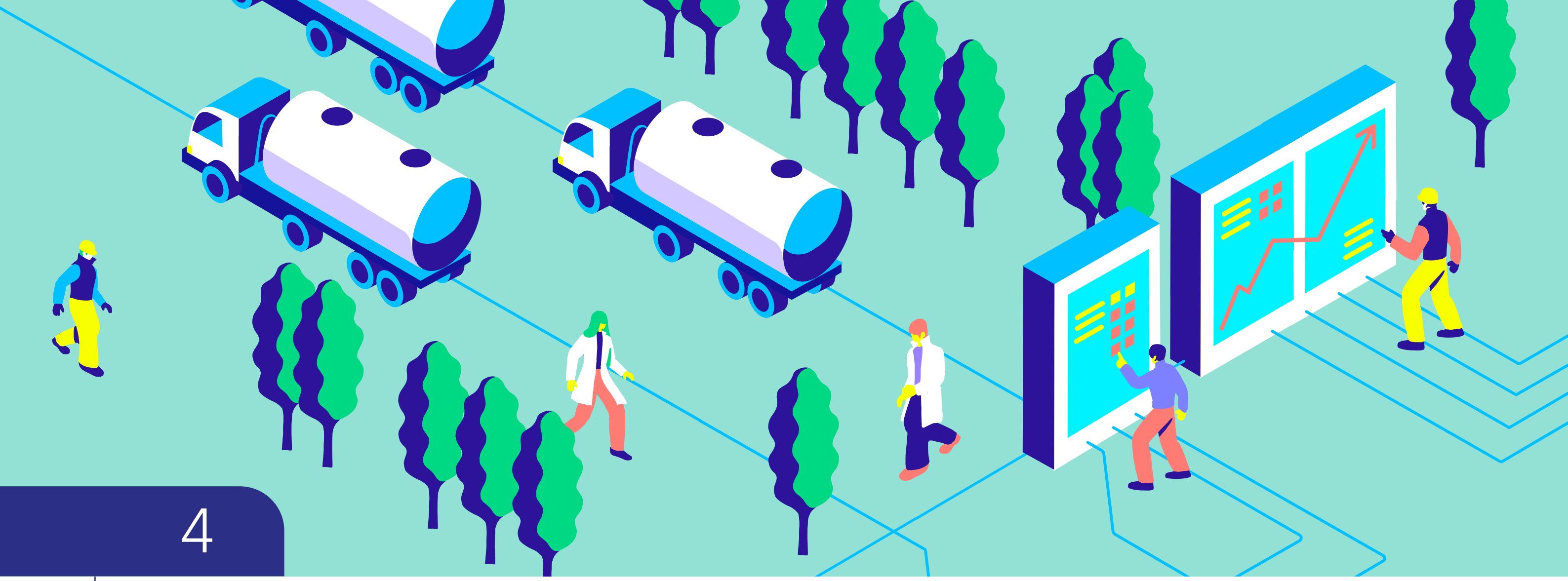
Stein (2020) advocates that the important aspects of accountability, safety and certification can be addressed through (a) avoiding "AI-washing", noting that it is imperative that "AI" not be used as a catchall for all matters involving data processing; and (b) having explainable AI, that is, if important policy decisions are to be based on the results of climate AI, it is imperative that there is trust in the system by addressing the actual legitimacy of the AI algorithm itself.

In summary, the following actions are proposed in order to aid the application of AI to address the global climate challenge:

- Promoting inter- and intra-country learning, including by identifying relevant skills, optimization of existing knowledge and capabilities, and developing new skills through targeted training;

- Fostering collaboration among all stakeholders, undertaking joint pilot activities and programmes, and listening and sharing knowledge and data sets from governments (policymakers), business communities, research and academia, AI experts and civil society groups;

- Consciously and systematically implementing and deploying AI tools to achieve the desired impacts.



4

CONCLUSIONS AND RECOMMENDATIONS

This technical paper responds to the mandate of the KCI to build awareness and understanding of Parties and other stakeholders to assess the economic impacts of potential new industries and businesses resulting from the implementation of response measures with a view to maximizing the positive and minimizing the negative impacts of the implementation of response measures.

As part of the research that under pins the paper, the authors have provided a concise definition of what constitutes emerging industries and businesses in the context of climate change, namely, “those productive entities (materials, goods and services) that do not have a fully matured operating ecosystem because they are at an early stage of development, but do have the potential to significantly contribute to the global deep decarbonization effort by changing the current trajectory of global GHG emissions towards net zero”. Even though the authors were conscious of the dimensions of climate change work covering the area of mitigation and adaptation, the discussions in this technical paper are limited to the impacts of implementing response measures (mitigation actions).

One of the principal goals of the paper (i.e. to maximize the positive and minimize the negative impacts of the implementation of the response measures) is addressed by proposing cross-cutting issues and policy enablers. Originally, the paper was intended to address only the economic impacts of the emerging industries and businesses, but the restrictive scope of those impact categories was expanded to include both social and environmental impacts in order to ensure a more comprehensive and coherent treatment of the subject and to be consistent with the triple bottom line for sustainable development.

Desktop and systematic literature searches were carried out. The literature search was conducted using keywords and search strings, allowing the author to produce a table covering a broad list of emerging industries and businesses; and these were further shortlisted using criteria informed by predefined questions consistent with the theory of change. Three emerging industries and businesses – CCUS, hydrogen and AI – were identified and their corresponding social, economic and environmental impacts were reviewed.

This paper considers the impacts of CCUS, hydrogen and AI by looking at the scope and technology information presented in the existing literature to better understand their associated impacts. The paper also emphasizes the need to explore the possible benefits arising from a combination of several emerging industries and businesses through their multiplicative impacts.

4.1. Specific findings for the identified emerging industries and businesses

4.1.1. Carbon capture, utilization and storage

The major benefits of the large-scale investment in and deployment of CCUS and the existing evidence related to the value of CCUS are attributed to three overarching themes, as follows.

- CCUS is **an essential technology to economically meet long-term climate targets** and for risk mitigation through:
  - Achieving deep decarbonization in the hard-to-abate industries;
  - Enabling the production of clean hydrogen at scale;
  - Providing low-carbon dispatchable power;
  - Delivering negative emissions.
- CCUS is **a driver of economic growth and employment** by:
  - Creating and sustaining jobs;
  - Supporting economic growth through new net-zero industries and innovation spillovers;
  - Facilitating a just transition by alleviating geographical and timing mismatches;
  - Enabling the reuse of infrastructure and deferral of decommissioning costs.

The versatility of CCUS and its ability to reduce both the flow and stock of CO_2 makes it **a strategic risk management tool for climate mitigation**.

It is important to note that limiting the availability of CCUS would considerably increase the cost and complexity of the energy transition towards net zero emissions by increasing reliance on technologies that are currently more expensive and at earlier stages of development.

In addition, the AR6 (IPCC, 2022) warns that "practically all long-lived technologies and investments that cannot be adapted to low-carbon and net zero emission modes could face stranding under climate policy." It suggests that carbon-intensive facilities could be adapted by pairing them with CCUS technologies to prevent them from becoming "stranded assets" prematurely, which would increase transition costs and reduce public acceptance.

4.1.2. Hydrogen production

Hydrogen is a clean energy carrier and a primary energy source, and it can be used as a fuel in transportation, electricity production and as a feedstock in industry. As such, hydrogen offers a range of benefits for simultaneously decarbonizing the transport, residential, commercial and industrial sectors.

Hydrogen is one of the keys to the energy transition and sector-coupled energy system. Hydrogen is popular because of its high energy content, environmental compatibility, and ease of storage and distribution. It has the potential to cut emissions from hard-to-abate sectors such as heavy industry and transport.

The decision to promote hydrogen over other energy systems arises from the following facts: (a) it is the only option for at-scale decarbonization of certain segments in the transport, industry and building sectors; (b) it plays a systemic role in the transition to renewable energy sources by providing a mechanism to flexibly transfer energy across sectors, time and place; and (c) the transition to hydrogen is aligned with customer preferences and convenience. The latter is key because low-carbon alternatives that do not meet customer preferences will likely face adoption difficulties.

Hydrogen provides both a mechanism for sector coupling and the option to store energy at large scale over long periods of time or transport it from regions of supply to centres of demand. In transitioning to the hydrogen economy, however, cost-effective production methods, policies, regulatory frameworks (including codes and standards), research and development, and (above all) hydrogen infrastructure development are areas that need to be investigated in detail to inform investment decision-making. Hydrogen purification and compression (subsystems) are additional issues that need to be considered alongside the LCA when selecting the production method for hydrogen.

Given its suitability across a range of energy applications and carbon neutrality at the point of use, hydrogen is regarded as a "green" energy vector that offers a unique cross-system opportunity for fundamental change in the energy landscape. However, this will require continuous efforts on performance improvements, scale ramp-up, technical prospects and political support to enable a cost-competitive hydrogen economy.

4.1.3. Artificial intelligence

AI seems particularly fitting for addressing climate change questions, an area rife with massive data challenges. Monitoring sources and emissions of GHGs has been happening for decades, but the data remain difficult to parse, analyse and use productively. AI can also help predict where carbon emissions will come from, which can help policymakers and financiers on decisions about how and where to regulate and invest in energy production, for example. AI offers reliability, and cost-effectiveness, solves complicated problems and makes decisions; in addition, AI restricts data from getting lost. AI is applied nowadays in most fields, including business and engineering.

One of the most significant tools used by AI is “reinforcement learning”, which is based on testing success and failure in real life to increase the reliability of applications.

The nature of climate-relevant data poses challenges and opportunities. The use of technologies and intelligent system design has the potential to restore and regenerate the natural environment.

4.2. Policy recommendations

This section provides a non-exhaustive list of policy recommendations relating to the three

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shortlisted emerging industries and businesses. In the context of policy recommendations, it is important to note that engagement of the private sector, including small and medium-sized enterprises, is a cross-cutting issue that could facilitate identification and exchange of experiences and best practices to promote the creation of decent work and quality jobs in the emerging low GHG emission sectors.

4.2.1. Carbon capture, utilization and storage

- Develop a regulatory framework for CO_2 capture, transport, utilization and storage at the national and/or global level, consistent with national circumstances. Such a framework will help to ensure standardization of the design and application of CCUS with high safety standard;
- Strengthen policy support for CCUS to drive innovation and deployment. This is central to the scaling up of CCUS. As CCUS technology matures, specific policy incentives are critical to expand the frontier of the market worldwide;
- Promote the effective application and use of CCUS to stimulate early achievement of net zero emissions and help keep the world on track towards the 1.5–2 °C goal, while avoiding the risk of stranded assets under national/global climate policy environment.

4.2.2. Hydrogen production

The climate community and governments can play a crucial role in creating the necessary enabling environment by working together as follows:

- Ensure that mega funds that have been ring-fenced for climate technologies are accessible to developing countries to support hydrogen economy programmes;
- Collaborate on adopting a uniform methodology for calculating life cycle GHG emissions for hydrogen, and on developing comprehensive and science-based terminology, as well as standards or best practices for the deployment of hydrogen;
- Expand collaboration on sustainable hydrogen production across all regions and call for the development of a sustainable hydrogen market by developing market stimulation programmes;
- Develop a tradable GOH to decouple physical from commercial flows and accelerate hydrogen deployment worldwide;
- Develop relevant codes and standards to promote widespread adoption of the hydrogen economy;
- Put in place the necessary systemic, legal and regulatory frameworks;
- Develop bespoke institutional capacity-building and training packages to support the transition to the hydrogen economy;
- Establish state ministries to support the transition to the hydrogen economy, including infrastructure development and service delivery;
- Undertake scientific assessments to identify the national resource endowment potential for sustainable hydrogen production;
- Promote decentralized production and use of hydrogen in the energy, industry and transport sectors, with a view to achieving net-zero emissions growth;
- Develop systems for sustainable and transformational impacts monitoring, reporting and verification consistent with the enhanced transparency framework under the Paris Agreement;
- Support research and development as well as knowledge management infrastructure to promote peer-to-peer learning;
- Undertake economic and financial analyses, including assessment of diversification of investments and business models for investment in the hydrogen economy;
- Promote partnerships involving relevant national and international stakeholders from the public and the private sectors, as well as from civil society and the research and academic communities.

4.2.3. Artificial intelligence

The following will aid the application of AI to address climate challenge:

- Promote inter- and intra-country learning, including by identifying relevant skills, optimization of existing knowledge and capabilities, and developing new skills through targeted training;
- Foster collaboration among all stakeholders, including undertaking joint pilot activities and programmes, and listening and sharing knowledge and data sets from governments (policymakers), business communities, research and academia, AI experts and civil society groups;
- Consciously and systematically implement and deploy AI tools to achieve the desired impacts.

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United Nations Climate Change
Katowice Committee on Impacts

Katowice Committee of Experts on the Impacts of the Implementation of Response Measures is a constituted body which was established in Katowice December 2018 to support the work programme of the forum on the impact of the implementation of response measures.

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