Alliance for Industry Decarbonization

Advancing bioenergy with carbon capture, utilisation and storage

Policies, regulations, MRV and certification

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About AFID

The mission of the Alliance for Industry Decarbonization is to foster action for decarbonisation of industrial value chains and to promote understanding of renewables-based solutions and their adoption by industry, with a view to contributing to country-specific net-zero goals. AFID is open for members and ecosystem knowledge partners to any legal entity engaged in decarbonising industry based on renewable energy solutions. This can include but is not limited to public or private sector industrial firms, industry associations, the financial community and inter-governmental organisations.

The International Renewable Energy Agency (IRENA) co-ordinates and facilitates the activities of AFID.

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About this report

The development of this report was led by the United Nations Industrial Development Organization (UNIDO) as an AFID ecosystem partner and was supported by members of the AFID working group BECCUS. It builds on exchanges and discussions among the working group members that took place during a series of meetings to realise joint initiatives. This report is informed by the experience of UNIDO and AFID members from different regions across the world.

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Disclaimer

Contents

Figures 3

Tables 3

Boxes 3

Abbreviations 4

01 Introduction and background 5

02 Policies supporting CCUS 8

Best practices in overarching policy positions 8

Policy frameworks and best practices for BECCS 10

National commitments and inclusion of CCUS in Nationally Determined Contributions 10

National finance mechanisms for Technological Readiness Level enhancement 12

Fiscal incentives and financing mechanisms 13

Shared infrastructure and public-private partnerships 15

03 Regulations governing CCUS operations 16

Background 16

Types and scope of regulations required 16

Best practices in regulatory frameworks 18

Liability concepts and financial guarantees management 21

Critical regulatory gaps and required actions 23

04 Methodologies and standards for MRV and certification of carbon credits 25

Background 25

Certification landscape: National (compliance) versus voluntary schemes 26

Best practices in MRV and certification 28

Carbon trading systems and their implications for CCUS 29

Critical gaps in certification processes 30

Accounting for BECCS as a negative emission technology 31

05 The role of bioenergy and BECCUS 33

Bioenergy supply and consumption 33

Biomass supply chain 34

Bioenergy policy framework 36

Integration of bioenergy with CCS and CCUS in policy frameworks 37

06 Conclusions and recommendations 38

CCUS policies 38

CCUS regulations 38

Methodologies and standards for MRV and certification of carbon credits 39

07 References 40

Figures

Figure 1	Bioenergy final energy consumption by sector in 2020, 2030 and 2050 under the Planned Energy Scenario and the 1.5°C Scenario	33
Figure 2	A policy framework for sustainable bioenergy development	36

Tables

Table 1	Examples of CCUS policy developments in different geographical regions	9
Table 2	Countries with CCUS included in their Nationally Determined Contributions as of 2022	11
Table 3	National and regional fiscal incentives for CCUS and CCS	14
Table 4	Potential CCUS hubs	15
Table 5	CCUS regulatory frameworks best practices	19
Table 6	Financial assurance mechanisms for CCUS projects	22
Table 7	Regulatory and engagement gaps with corrective actions	23
Table 8	Illustrative CCUS certification mechanisms	27
Table 9	Key best practices in MRV and certification	28
Table 10	Carbon trading systems implications for CCUS	29
Table 11	Certification processes critical gaps	30
Table 12	BECCS components and accounting of net negative emissions	31
Table 13	Biomass supply systems challenges	35

Boxes

Box 1	Note on definitions for CCUS, BECCS and BECCUS	7

Abbreviations

°C	degrees Celsius
BECCS	bioenergy with carbon capture and storage
BECCUS	bioenergy with carbon capture, utilisation and storage
BSC	biomass supply chain
CAD	Canadian dollar
CCS	carbon capture and storage
CCS Directive	Carbon Capture and Storage Directive (EU)
CCUS	carbon capture, utilisation and storage
CCUS-ITC	CCUS investment tax credit (Canada)
CDR	carbon dioxide removal
CEPA	Canadian Environmental Protection Act
CO_2	carbon dioxide
DOE	US Department of Energy
EPA	US Environmental Protection Agency
ETS	emissions trading system
EU	European Union
EU ETS	EU Emissions Trading System
EUR	euro
GBP	British pound
IEA	International Energy Agency
IRA	US Inflation Reduction Act
IRENA	International Renewable Energy Agency
JCM	Joint Crediting Mechanism
LCA	life-cycle assessment
MRV	monitoring, reporting and verification
NDC	Nationally Determined Contribution
NOK	Norwegian krone
PPP	public-private partnership
PSA	Petroleum Safety Authority (Norway)
RD&D	research, development and deployment
SDG	Sustainable Development Goal
TRL	Technology Readiness Level
UK	United Kingdom
US	United States
USD	United States dollar
VCS	Verified Carbon Standard

1 Introduction and background

In the battle against climate change, the pivotal role of bioenergy with carbon capture, utilisation and storage (BECCUS) has come into sharp focus. An increase in the production and use of modern bioenergy will be essential for the global shift to low-carbon and net-zero emission pathways. The 1.5°C Scenario developed by the International Renewable Energy Agency (IRENA) indicates that bioenergy production must grow substantially by 2050 to meet the international climate goal of keeping global temperature rise below 1.5 degrees Celsius (°C) of pre-industrial levels. BECCUS has an indispensable role to play in deep decarbonisation strategies, particularly in industrial sectors where carbon dioxide (CO_2) emissions from existing fossil fuel-based energy production cannot be credibly substituted with renewable energy, and in sectors that generate significant process-related emissions.

BECCUS specifically targets the integration of biomass with carbon capture, utilisation and storage (CCUS) technologies to achieve negative emissions. However, CCUS itself encompasses a broader suite of technologies aimed at reducing greenhouse gas emissions across various sectors. Its core principles encompass the capture of CO_2 emissions, their use in various applications, and their secure, long-term underground storage. This integrated approach offers a multi-pronged solution. It not only greatly reduces emissions, but also contributes to the removal of CO_2 from the atmosphere – an imperative in the quest for net-zero emissions.

The urgency of addressing climate change head-on has led to widespread recognition that CCUS is a requirement in global environmental strategies. Although it has not been universally endorsed, many governments, industries and organisations worldwide have rallied behind CCUS, propelling the development of comprehensive policies, regulations and certification mechanisms that underpin its deployment, operation and scrutiny. This report explores the landscape of CCUS initiatives, offering a broad understanding of the efforts driving its advancement globally.

BECCUS represents a promising approach to CO_2 mitigation by combining bioenergy production with CCUS technology. This innovative process involves using biomass, such as agricultural residues or dedicated energy crops, to generate renewable energy while capturing CO_2 emissions from biomass combustion or biofuel production. The captured CO_2 is then transported and securely stored underground, preventing its release into the atmosphere and effectively removing CO_2 from the atmosphere on a net basis. BECCUS not only offers a sustainable source of energy but also contributes to negative emissions, making it a potentially useful tool in achieving climate targets and addressing global warming.

However, challenges remain in scaling up BECCUS deployment, including sustainable biomass sourcing, technological optimisation, use of CO_2 and ensuring long-term storage integrity. Efforts to overcome these challenges are crucial for unlocking the full potential of BECCUS in the transition towards a low-carbon economy. Furthermore, the development of supportive policies and regulations tailored to BECCUS implementation is essential to incentivise investment, ensure sustainability in biomass sourcing and provide a clear framework for CCUS activities.

This report covers topics related to bioenergy, policies promoting CCUS, regulations governing CCUS operation, methodologies, and standards for monitoring, reporting and verification (MRV) and carbon credit certification. The report also assesses best practices in policy positions, national commitments, financial mechanisms, fiscal incentives and the dynamics of public-private partnerships (PPPs). The analysis examines the key roles that all these elements play in fostering CCUS adoption and policy gaps, and charts a course for necessary action.

Effective regulatory frameworks are the bedrock of safe and efficient CCUS operations. The report analyses the diverse types and scopes of necessary regulations, best practices from around the world, liability concepts and the difficulties of financial guarantees management. It delineates critical regulatory gaps and areas requiring immediate and sustained regulatory intervention.

In relation to MRV systems and certification, the report spotlights the interface between national and voluntary certification schemes. Certification mechanisms are assessed in both the public and private domains, as well as the scope and reach of existing certification mechanisms. The report discusses best practices in MRV and the implications of carbon trading systems for CCUS. Gaps in certification processes are identified, as well as solutions to close them.

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Additionally, this report often mentions bioenergy with carbon capture and storage (BECCS); however, it is important to recognise that BECCS is actually part of the broader BECCUS framework (see Box 1). BECCUS goes beyond capturing and storing CO_2; it also focuses on *utilising* the captured carbon, which is becoming increasingly relevant for both environmental and economic reasons. While the report covers various aspects of CCUS and CCS, it focuses primarily on how these technologies apply specifically to bioenergy through BECCUS, particularly in achieving negative emissions.

In conclusion, the report synthesises key findings and their implications. It outlines a set of pragmatic recommendations that provide a pathway for stakeholders committed to climate change mitigation.

Around the world, countries are grappling with the imperative to transition towards a low-carbon future. This report aims to offer insights, knowledge and actionable guidance to policy makers, industry leaders and environmental advocates who are interested in realising the potential of bioenergy with CCUS in the fight against climate change.

BOX 1 Note on definitions for CCUS, BECCS and BECCUS

In the context of industrial decarbonisation, it is crucial to differentiate between various CO_2 solutions, as each provides distinct pathways to reducing emissions. The following definitions clarify the roles of CCS, CCU, BECCS and BECCUS, which are key components in achieving decarbonisation goals (IEA, 2024a; Lyons *et al.*, 2021).

CCS (carbon capture and storage) involves the direct capture of CO_2 emissions from point sources, such as fossil fuel use or industrial operations, with the captured CO_2 then stored for long-term containment.

CCU (carbon capture and utilisation), on the other hand, focuses on using the captured CO_2 in secondary processes, such as creating synthetic fuels, chemicals or other materials.

BECCS (bioenergy with carbon capture and storage) integrates bioenergy into this process. Biomass absorbs CO_2 as it grows, and when used for energy or industrial purposes, the CO_2 released is captured and stored. BECCS uses similar technology to CCS but relies on renewable, biogenic materials.

BECCUS (bioenergy with carbon capture, utilisation and storage) expands on this by capturing, storing or utilising biogenic CO_2 from activities such as bioethanol production or biogas upgrading. It also applies to processes beyond energy generation and is sometimes referred to as BECCS/U or Bio-CCUS.

2 Policies supporting CCUS

2.1 Best practices in overarching policy positions

Effective CCUS policies will be necessary for the successful deployment and adoption of these technologies. Table 1 provides examples of policy developments in different geographical regions. Best practices in shaping overarching policy positions include:

- **Clear emission reduction targets:** Policies should define precise goals for emission reduction, aligning with international climate agreements and setting dedicated targets for CCUS. For example, the commitment by the European Union (EU) to achieve net-zero greenhouse gas emissions by 2050 sends a clear signal to industries and investors to decarbonise. The new European Industrial Carbon Management Strategy, which defines a clear strategy for CCUS, has the potential to encourage wider CCUS development (EC, 2024).
- **Regulatory certainty:** Governments must provide a stable regulatory environment that encourages long-term investments. Norway's transparent and predictable regulatory framework has attracted significant CCUS investments. For example, companies such as Equinor and TotalEnergies have made substantial commitments to develop CCUS projects in Norway due to this regulatory certainty (IEA, 2022a).
- **Stakeholder collaboration:** Policy makers should facilitate collaboration among governments, industries and research institutions. The Porthos project in the Netherlands exemplifies a successful public-private partnership (PPP) in CCUS (Porthos, 2023).

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TABLE 1 Examples of CCUS policy developments in different geographical regions

Country/region	CCUS policy examples
United States	The national climate goals of 100% clean electricity by 2035 and achieving a net-zero emissions economy by 2050 include the use of CCS (DOE, 2023a: 100). The US Infrastructure Investment and Jobs Act, passed into law in 2021, allocates more than USD 12 billion for CCS and related activities, including carbon storage validation, hydrogen hubs and CCS technology development. The Inflation Reduction Act enhanced the 45Q tax credit for CCS and accelerated its deployment (GCCSI, 2022). At the state level, several US states including California, North Dakota, Pennsylvania and West Virginia have advanced legislation and programmes related to CO_2 storage and CCS support (GCCSI, 2022).
Canada	In 2022, the federal government released its 2030 Emissions Reduction Plan, which provides a roadmap for Canada to meet the enhanced target set in its Nationally Determined Contribution (NDC) under the Paris Agreement. This target aims to reduce Canada's greenhouse gas emissions 40-45% below 2005 levels by 2030 and puts the country on a path to achieving net-zero emissions by 2050 (Government of Canada, 2023). Canada's 2022 federal budget strongly supported CCUS via an investment tax credit (CCUS-ITC). The CCUS-ITC is for 37.5% to 60% of the project value from 2022 through 2030. To encourage industry to move quickly to lower emissions, the CCUS-ITC is reduced by 50% for the period 2031-2040. Companies can only qualify for the tax credit if they commit to following a validation and verification process (IEA, 2022b). In 2021, the province of Alberta announced the Hydrogen Roadmap, which includes CCUS as a key component (Government of Alberta, 2023).
European Union	Denmark announced EUR 5 billion (USD 5.4 billion) in subsidies for CCS (GCCSI, 2022). Norway allocated NOK 1 billion (USD 91.2 million) for blue hydrogen projects, and several CCS projects received grants under the EU's Innovation Fund (Reuters, 2021). The EU's Innovation fund is supporting CCS projects via the monetisation of revenues from allowances under the EU Emissions Trading System (EU ETS). The EU supports the design and construction of CO_2 transport and storage infrastructure through the Connecting Europe Facility funding programme, available for Projects of Common Interest. The Net-Zero Industry Act, proposed in March 2023, provides an initial framework including an EU-wide CO_2 storage target, and in February 2024 the EU adopted a regional strategy for CCUS, announced as the Industrial Carbon Management Strategy (EC, 2024).
United Kingdom	In 2022, the UK government released its CCUS Investor Roadmap outlining plans for four low-carbon industrial clusters by 2030. The selected clusters are East Coast Cluster and HyNet (Track 1) and Acorn and Viking T&S systems (Track 2). In March 2023, the UK government committed to allocating GBP 20 billion (USD 25.9 billion) for CCUS projects over the next 20 years (UK Government, 2023a).
Asia-Pacific	The Asia-Pacific region, including Australia, China, India, Indonesia, Japan, Malaysia and Thailand, is also advancing CCS policies (GCCSI, 2022; Mukherjee, Atanu and Chatterjee, Saurav, 2022). Japan introduced new climate and energy policies and also released its CCS Long-Term Roadmap, which aims to boost the deployment of CCS technologies by targeting commercial deployment by 2030 (METI, 2023). South-East Asia has significant CCS potential, with Indonesia and Malaysia making policy announcements and developing CCS-specific legal and regulatory frameworks to incentivise CCS projects (GCCSI, 2022).
China	In 2021, China introduced its 30/60 climate policy framework, setting the targets of reaching carbon peaking by 2030 and climate neutrality by 2060. The 1+N framework provides some of the groundwork for CCUS policy directions (CCC, 2021). The People's Bank of China launched a carbon emission reduction facility, a structural monetary policy instrument designed to provide financial institutions with low-cost loans aimed at supporting decarbonisation projects, including CCUS initiatives.

2.2 Policy frameworks and best practices for BECCS

Policy incentives are crucial to bolster a diverse array of carbon removal options, particularly in the case of bioenergy with carbon capture and storage (BECCS), which necessitates close collaboration with land-use and agriculture policies. To effectively scale up engineered carbon removal technologies such as BECCS, specific policies tailored to address their capital-intensive and risky nature are indispensable.

Generic policies such as carbon pricing prove inadequate in this context. Instead, a gradual and cautious approach through deployment contracts for BECCS is warranted. Moreover, policy support for BECCS must be contingent upon rigorous evaluation and performance assessment, encompassing factors such as costs, technical efficacy, life-cycle emissions and sustainability. If BECCS fails to meet carbon removal targets effectively, the government should prioritise efforts to curtail residual emissions and redirect support towards alternative carbon removal options. An overarching strengthening of evaluation mechanisms within innovation programmes is imperative, ensuring that ongoing assessment and adjustment occur as policies are implemented (UCL, 2020).

Policy approaches to carbon dioxide removal (CDR) – such as BECCS that captures biogenic CO_2 at the point of emission and sequesters it to achieve net negative emissions – necessitate transparent frameworks to showcase the climate benefits and foster stakeholder trust. Internationally recognised standards are crucial for integrating CDR into existing regulations. For example, in November 2022 the European Commission adopted a voluntary certification framework to verify high-quality carbon removals, emphasising quantification, additionality, long-term storage and sustainability.

In Denmark, the NECCS Fund offers subsidies for negative emissions from CO_2 capture of biogenic sources and subsequent geological storage. Meanwhile, the Hydrogen BECCS Innovation Programme in the United Kingdom supports hydrogen production technologies from biogenic feedstocks that are combined with carbon capture. This multi-phase programme provides funding for innovative projects to advance commercially viable solutions, reflecting the growing commitment to carbon removal and climate mitigation efforts (IEA, 2024a).

In addition, CCUS-related policies and finance mechanisms in multiple countries support BECCS applications. For example, the Danish Energy Agency is consulting market participants for a subsidy scheme targeted at negative emissions. The US Inflation Reduction Act promotes BECCS by offering tax credits valued at USD 60 per tonne of CO_2 utilised and USD 85 per tonne of CO_2 stored. In 2022, the United Kingdom launched the Hydrogen BECCS Innovation Programme, which plans to allocate more than GBP 30 million (USD 38.9 million) in funding across two phases.

2.3 National commitments and inclusion of CCUS in Nationally Determined Contributions

Incorporating CCUS into national commitments and NDCs signifies a country's commitment to these technologies and sets the stage for their widespread adoption. Prominent examples include:

- The United States is committed to deploying CCUS as a critical climate mitigation tool. The US Infrastructure Investment and Job Act, signed into law in 2021, allocated substantial funds for research, development and commercialisation of CCUS technologies. This commitment reflects bi-partisan recognition of the significance of CCUS in addressing climate change.
- The United Kingdom has included CCUS in its NDCs, demonstrating dedication to achieving net-zero greenhouse gas emissions by 2050. The CCS Infrastructure Fund launched by the UK government aims to support CCUS infrastructure development, exemplifying its commitment to the technology.
- Canada, as part of its Pan-Canadian Framework on Clean Growth and Climate Change, recognises the importance of CCUS. The federal government's support for CCUS projects, such as the Boundary Dam 3 project in Saskatchewan, underscores its commitment to reducing emissions.
- Norway has a strong commitment to CCUS, evident through its Longship project. This project includes the capture and storage of CO_2 from industrial facilities and power generation, positioning Norway as a global leader in CCUS technology.

- Australia's commitment to CCUS is demonstrated through the Carbon Capture Use and Storage Development Fund, which supports CCUS projects across the country. The Gorgon Carbon Dioxide Injection Project, supported by this fund, has demonstrated the feasibility of large-scale geologic storage of CO_2.
- The Middle East and North Africa region, notably Saudi Arabia and the United Arab Emirates, has recognised the potential of CCUS. Both countries have integrated CCUS projects into their national strategies for emission reduction.

Table 2 lists the 22 countries that had included CCUS in their NDCs as of the release of the *Global status of CCS 2022* report (GCCSI, 2022). Since then, more countries have announced the inclusion of CCS in their NDCs, increasing the total number of countries to 27 as of 2023 (IEA, 2023a). According to the International Energy Agency (IEA), the list of countries that include CCS in their NDCs has been extended to include Australia, Bahrain, Canada, China, Iceland, Japan, Morocco, Norway, Saudi Arabia, Türkiye, the United Arab Emirates, the United Kingdom, the United States and Viet Nam (IEA, 2023a).

TABLE 2 Countries with CCUS included in their Nationally Determined Contributions as of 2022

YEAR	INDC	FIRST NDC	FIRST NDC UPDATE	SECOND NDC
AUSTRALIA	NOT AVAILABLE	NDC DOES NOT MENTION CCS	NDC MENTIONS CCS	
BAHRAIN	NOT AVAILABLE	NDC MENTIONS CCS	NDC MENTIONS CCS	
CANADA	NDC MENTIONS CCS	NDC DOES NOT MENTION CCS	NDC MENTIONS CCS	
CHINA	NDC MENTIONS CCS	NDC MENTIONS CCS	NDC MENTIONS CCS	
EGYPT	NOT AVAILABLE	NDC MENTIONS CCS		
EL SALVADOR	NOT AVAILABLE	NOT AVAILABLE	NDC MENTIONS CCS	
ICELAND	NOT AVAILABLE	NOT AVAILABLE	NDC MENTIONS CCS	
ISLAMIC REPUBLIC OF IRAN	NDC MENTIONS CCS			
IRAQ	NDC MENTIONS CCS			
JAPAN	NOT AVAILABLE	NOT AVAILABLE	NDC MENTIONS CCS	
MALAWI	NDC MENTIONS CCS	NDC MENTIONS CCS	NDC MENTIONS CCS	
MONGOLIA	NDC DOES NOT MENTION CCS	NDC DOES NOT MENTION CCS	NDC MENTIONS CCS	
NORWAY	NOT AVAILABLE	NDC MENTIONS CCS	NDC MENTIONS CCS	
PAKISTAN	NOT AVAILABLE	NOT AVAILABLE	NDC MENTIONS CCS	
QATAR	NOT AVAILABLE	NOT AVAILABLE	NDC MENTIONS CCS	
SAUDI ARABIA	NDC MENTIONS CCS	NDC MENTIONS CCS	NDC MENTIONS CCS	
SOUTH AFRICA	NDC MENTIONS CCS	NDC MENTIONS CCS	NDC DOES NOT MENTION CCS	
UAE	NOT AVAILABLE	NDC MENTIONS CCS	NOT AVAILABLE	NDC MENTIONS CCS
UNITED STATES	NDC DOES NOT MENTION CCS	NDC MENTIONS CCS		
KUWAIT	NOT AVAILABLE	NDC DOES NOT MENTION CCS	NDC MENTIONS CCS	
TOGO	NOT AVAILABLE	NOT AVAILABLE	NDC MENTIONS CCS	
TUNISIA	NOT AVAILABLE	NDC DOES NOT MENTION CCS	NDC MENTIONS CCS	

■ NDC MENTIONS CCS ■ NDC DOES NOT MENTION CCS ■ NOT AVAILABLE

Source: (GCCSI, 2022).

Notes: UAE = United Arab Emirates.

2.4 National finance mechanisms for Technological Readiness Level enhancement

Governments can draw on a variety of mechanisms to finance the research, development and deployment (RD&D) of CCUS technologies. These mechanisms are typically designed to support projects at different stages of Technological Readiness Level (TRL)[1].

Some examples of national finance mechanisms for TRL enhancement in CCUS include:

- **Tax credits and deductions:** Governments can provide tax credits or deductions to companies that invest in CCUS research and development or that deploy CCUS technologies at scale. This can help to reduce the upfront costs of these technologies and make them more attractive to investors.
- **Grants and loans:** Governments can provide grants and loans to companies and researchers to support CCUS RD&D. This can be particularly helpful for early-stage projects that may not have access to traditional financing sources.
- **Public-private partnerships (PPPs):** Governments can partner with private companies to finance CCUS projects. This can help to leverage the resources and expertise of both sectors.
- **Dedicated CCUS funds:** Governments can establish dedicated funds to finance CCUS projects. This can help to ensure that there is a reliable source of funding for CCUS technologies, even during economic downturns.

Specific examples of national finance mechanisms for TRL enhancement in CCUS from around the world include:

- The US Department of Energy (DOE) provides a variety of funding opportunities for CCUS research and development, including the Carbon Capture Technology Program and the Advanced Fossil Energy Systems Program. The DOE also provides tax credits for the capture and storage or utilisation of CO_2 (DOE, 2023b).
- The Canadian government provides grants and loans for CCUS projects through the Clean Energy Technologies Program. The government also provides a tax credit for CCS projects (ICCSKC, 2023).
- The UK government provides funding for CCUS research and development through the Carbon Capture Usage and Storage Innovation Centre. The government also provides a CCS commercialisation competition (UK Government, 2023b).
- The Australian government provides funding for CCUS research and development through the Carbon Capture and Storage Research, Development and Demonstration Program. The government also provides a CCS investment tax credit (GCCSI, 2021).
- Japan's commitment to CCUS is evident through its Joint Crediting Mechanism (JCM). The JCM addresses two main purposes: Firstly, to accurately assess Japan's contributions to greenhouse gas emission reductions or removals achieved through the diffusion of low-carbon technologies, products, systems, services, and infrastructure, as well as the implementation of mitigation actions in developing countries. Secondly, to utilise these contributions to help Japan achieve its emission reduction target. The JCM has operated between Japan and Bangladesh, Cambodia, Chile, Costa Rica, Ethiopia, Indonesia, Kenya, Lao People's Democratic Republic, Maldives, Mexico, Mongolia, Myanmar, Palau, the Philippines, Saudi Arabia, Thailand and Viet Nam. The Petra Nova CCUS facility in the United States received support through the JCM, showcasing Japan's international collaboration in CCUS (MOFA, 2023).

[1] *Technological Readiness Levels (TRLs) is a methodology used to assess the maturity of a technology. The scale ranges from 1 (basic principles observed) to 9 (full commercial deployment), providing a systematic metric to evaluate the progression of technology from concept to commercialisation (EC, 2014).*

- At the EU level, Horizon Europe serves as a prominent funding programme that drives research and innovation across the region. It aims to support and advance cutting-edge scientific discoveries, technological developments and societal challenges. This includes fostering research in various areas, such as CCS. Through Horizon Europe Cluster 5: Climate, Energy, and Mobility, the European Commission supports the development of new CO_2 capture technologies and the enhancement of existing ones. The dedicated CCUS ZEN project facilitates the integration of CCS and CCU within hubs and clusters, while also promoting knowledge-sharing activities (EC, n.a).
- Norway's financial support for CCUS extends to around two-thirds of the total cost of the Longship project, a significant example of a PPP. The project aims to establish a full-scale CO_2 capture, transport and storage value chain in the North Sea, exemplifying Norway's commitment to cross-border CCUS initiatives (Norway Ministry of Petroleum and Energy, 2020).
- In Denmark, the Energy Technology Development and Demonstration Programme (EUDP) finances development and demonstration projects that use innovative technologies, including CCUS, that can contribute to the achievement of the Danish carbon emission reduction target. The Greensand and Bifrost CCS projects benefited from grants from this programme (ENS, 2023).
- The Republic of Korea's tax credit system incentivises private investment in CCUS projects (PwC, 2023). The K-CO2 project, which captures CO_2 emissions from a steel mill, benefited from these incentives.

Funding is targeting the RD&D of various BECCS applications, as well as specific commercial projects (IEA, 2024a):

- In the EU, two large-scale projects involving biogenic CO_2 capture were selected for funding under the EU Innovation Fund's 2021 call. These were the HySkies sustainable aviation fuel project, which sources CO_2 from a combined heat and power plant in Sweden (EUR 80 million or USD 86.8 million), and the Go4ECOPlanet cement project in Poland (EUR 228 million or USD 247.5 million).
- In Denmark, the first tender of the CCUS subsidy scheme, released in May 2023, awarded funding to a BECCS project with a capacity of 0.4 million tonnes of CO_2 per year. The project aims to capture CO_2 from two biomass-fired power stations for dedicated storage.
- In Canada, Emissions Reduction Alberta announced nearly CAD 2.5 million (USD 1.9 million) in funding in 2022 to explore the capture and storage of biogenic CO_2 emissions at West Fraser's Hinton Pulp Mill, with the goal of permanently removing 1.3 million tonnes of CO_2 per year.

2.5 Fiscal incentives and financing mechanisms

Fiscal incentives and innovative financing mechanisms can play a decisive role in encouraging the development of CCUS projects. The following are examples from diverse regions (see also Table 3):

- The EU's Emissions Trading Scheme (EU ETS) provides a price on carbon, indirectly incentivising CCUS deployment. The inclusion of CCUS in the Innovation Fund under the EU ETS supports innovative CCUS projects (EC, n.a).
- The US Inflation Reduction Act (IRA), passed in 2022, included a substantial change to the tax credits for the carbon capture industry. The IRA is intended to facilitate the achievement of a 40% reduction in US greenhouse gas emissions below the 2005 level by 2030, leading to the avoidance of 6.3 billion tonnes of cumulative emissions. With changes to the federal Section 45Q tax credit, the IRA effectively provides ten years of guaranteed incentives for carbon capture technology, including a 15% minimum tax on corporations that earn more than USD 1 billion in annual profits (ICCSKC, 2023).

- The Dutch government supports CCUS through the Sustainable Energy Production and Climate Transition Incentive Scheme (SDE++), which allocates funds in the form of contracts for difference on a competitive basis within a wide range of solutions for decarbonisation (NEA, 2023).
- The government of Canada has implemented the CCUS-ITC in October 2023 following public consultation on draft legislation released in August 2023. The CCUS-ITC is the government's centrepiece for incentivising heavy industries to build CCS projects by covering 50% of the capital cost of CO_2 capture projects between 2022 and 2030. The ITC is higher (60%) for projects that capture CO_2 directly from the atmosphere (direct air capture), and it also covers 37.5% of the cost for facilities required to transport, utilise and permanently store CO_2. The government of Canada offers carbon credits of up to CAD 170 (USD 122) per tonne of CO_2 sequestered. In addition, the Canadian government, through the Strategic Innovation Fund, supports CCUS projects such as the Quest CCS Facility in Alberta. This financial backing encourages technological advancements in CCUS (ICCSKC, 2023).
- China's commitment to CCUS is evident through various pilot projects. The Sinopec Qilu-CNOOC Bohai CCUS project demonstrates China's pursuit of CCUS solutions in the industrial sector (GCCSI, 2023).

TABLE 3 National and regional fiscal incentives for CCUS and CCS

Region	Fiscal incentive(s)
United States	Tax credits for CO_2 captured and stored, and CCUS research and development
Europe	Carbon pricing mechanisms, grants and subsidies
Canada	CCS investment tax credit; CCS operating expense tax credit
United Kingdom	CCS commercialisation competition; CCS commercialisation tax credit
Australia	CCS investment tax credit; CCS operating expense tax credit
China	Subsidies, tax breaks and preferential loans; CCUS fund
Norway	Tax breaks, investment grants and operating subsidies; CCUS cluster
Republic of Korea	Feed-in tariffs, subsidies and tax breaks; CCUS research and development
Saudi Arabia	Subsidies and CCUS research and development

2.6 Shared infrastructure and public-private partnerships

Shared infrastructure and PPPs are integral drivers in the progression of CCS projects, facilitating a collaborative environment among governments, industries and various stakeholders. Shared infrastructure encompasses the collective use of facilities and resources. This enables multiple entities to access and leverage common CCS infrastructure, thereby fostering cost reductions and operational efficiencies.

For their part, PPPs entail strategic collaborations between public entities and private enterprises, pooling resources, expertise and funding to foster the development and execution of CCS initiatives. These partnerships effectively capitalise on the combined strengths of both sectors, propelling technological advancements and encouraging the widespread adoption of CCS technologies.

- The EU fosters collaboration between private companies and Member States through Projects of Common Interest, key cross-border infrastructure projects that link the transport and storage systems of EU countries. One such initiative is Norway's Northern Lights, a joint venture associated with the Longship project that involves Equinor, Shell and TotalEnergies. It is aimed at creating shared CO_2 transport and storage infrastructure that can serve multiple industrial sites in northern Europe.
- In the United States, the Petra Nova project in Texas is a PPP between NRG Energy and JX Nippon Oil & Gas Exploration. This collaboration demonstrates the potential for private and public entities to work together in advancing CCUS.

Multiple announced projects utilise public and private funding with the aim of becoming CCUS hubs and shared facilities. Table 4 provides examples of CCUS projects that are designed or have the potential to become major CCUS hubs globally.

TABLE 4 Potential CCUS hubs

Region	CCUS shared infrastructure
Australia	Gorgon CCS Project
Canada	Boundary Dam and Quest CCS Projects
China	Yanchang CCS Project
Northern Europe	Northern Lights CCS Project
Republic of Korea	Pohang CCS Project
Saudi Arabia	Al Jubail CCS Project
United Kingdom	Shell Quest CCS project Hynet CCS Project Teesside Project Acorn project
United States	Petra Nova CCS Project

3 Regulations governing CCUS operations

3.1 Background

CCUS operations are subject to a variety of regulations, depending on the jurisdiction in which they are located. These regulations typically address issues such as:

- **Permitting and authorisation:** CCUS operators must typically obtain a permit or authorisation from the relevant regulatory authority before they can begin operations.
- **Site selection and characterisation:** CCUS operators must carefully select and characterise storage sites to ensure that they are safe and suitable for long-term storage of CO_2.
- **Monitoring and reporting:** CCUS operators must monitor CO_2 storage sites and report on their findings to the relevant regulatory authority.
- **Financial assurance:** CCUS operators must provide financial assurance to cover the costs of long-term site stewardship and liability.

In addition to these general regulations, CCUS operations may be subject to specific regulations related to the capture, transport and storage of CO_2. For example, CCUS operators may be required to meet certain standards for CO_2 purity and to follow certain procedures for transporting CO_2 safely.

The regulatory landscape for CCUS is constantly evolving. As CCUS technologies mature and are deployed more widely, governments are developing new regulations and updating existing regulations to ensure that CCUS operations are conducted safely and responsibly.

3.2 Types and scope of regulations required

Regulations for CCUS projects are essential to ensure environmental safety, operational standards and legal compliance. Types of regulations and their scope include the following:

1) Environmental regulations (EPA, 2021):
   - Emission limits – regulations governing the maximum allowable emissions of CO_2 and other pollutants from CCUS facilities. These limits ensure that captured CO_2 is safely stored and does not negatively impact air quality.
   - Waste disposal – rules for the safe disposal of by-products, such as brine or impurities from the carbon capture process, to prevent environmental contamination.
   - Water use – regulations regarding water intake, discharge and recycling to minimise the environmental impact of CCUS operations.
2) Safety regulations (IEA, 2020):
   - Well integrity – standards ensuring the secure and proper sealing of injection wells used for CO_2 storage to prevent leaks.
   - Monitoring and reporting – requirements for continuous monitoring of storage sites and prompt reporting of any issues to relevant authorities.
   - Emergency response – guidelines for responding to leaks or accidents during CCUS operations.
3) Regulations on ownership and liability (GCCSI, 2018):
   - Ownership regime for sub-surface storage – establishes ownership of the sub-surface geological area, typically through legislative or common law frameworks, outlining clear property interests, tenements and rights pertaining to stored CO_2.
   - Liability – rules determining liability in the case of accidents, leaks or damage related to CCUS activities.

4) Permitting and licensing regulations (DOE, 2017):

- CCUS project approval – procedures for obtaining permits and licences for CCUS projects, including environmental impact assessments.
- Storage rights – regulations specifying the allocation and use of sub-surface storage rights for CO_2 injection.

5) Transport regulations (PHMSA, 2020):

- Pipeline safety – regulations governing the safe design, construction, operation and maintenance of CO_2 pipelines used for transport.
- Transport permits – requirements for obtaining permits to transport captured CO_2 via pipelines or other means.

6) Injection regulations (EPA, 2021):

- Injection well design – requirements for the design and construction of injection wells, including specifications for materials and construction techniques to ensure well integrity.
- Injection pressure limits – regulations specifying the maximum allowable injection pressures to prevent over-pressurisation of the storage reservoir.
- Injection fluid composition – rules governing the composition of fluids used for CO_2 injection, ensuring compatibility with the geological formation.

7) Site selection and characterisation regulations (GCCSI, 2018):

- Geological assessment – requirements for comprehensive geological assessments of potential storage sites to determine their suitability for CO_2 injection.
- Environmental impact assessments – regulations mandating environmental impact assessments to evaluate the potential effects of CCUS projects on surrounding ecosystems.
- Public consultation – guidelines for involving stakeholders and local communities in the site selection and characterisation process.

8) Pre-injection regulations (USGS, 2018):

- Site preparation – regulations outlining the proper preparation of the storage site, including wellbore cleaning and formation conditioning before injection.
- Risk assessment – requirements for conducting risk assessments to identify potential hazards and develop mitigation strategies prior to injection.

9) Post-injection regulations (CCSA, 2020):

- Monitoring and verification – regulations mandating the ongoing monitoring and verification of CO_2 storage sites to ensure containment and assess their long-term effectiveness.
- Site closure and abandonment – guidelines for site closure and abandonment procedures, including well plugging and site decommissioning once injection is complete.
- Long-term ownership and liability – regulations addressing long-term liability and responsibilities for site maintenance and monitoring after project closure.

10) BECCS-specific regulations:

- Regulations for biomass sustainability need to be reformed and extended to address the entire supply chain, covering biomass sourcing, energy production, and CO_2 capture for utilisation or storage Assuming carbon neutrality solely at the point of combustion is misleading. This also requires aligning regulations across borders and including land-use changes in carbon accounting rules (CCSA, 2020).
- The CCS+ Initiative (CCS+, 2023) has introduced a proposed regulation to measure, monitor and verify carbon removals using methods such as Direct Air Capture (DACS), BECCS, and sustainable carbon farming practices like afforestation, reforestation and various agricultural techniques. The regulation sets clear guidelines for independent verification of carbon removals and recognition of certification schemes, focusing on four key pillars: quantification, additionality, long-term storage and sustainability.

3.3 Best practices in regulatory frameworks

In the United States, the US Environmental Protection Agency (EPA) regulates CCUS operations under the Clean Air Act and the Resource Conservation and Recovery Act (RCRA). The EPA has developed specific regulations for CCS, including requirements for permitting, site selection and characterisation, monitoring and reporting, and financial assurance.

The Canadian government regulates CCUS operations under the Canadian Environmental Protection Act (CEPA). CEPA requires CCUS operators to obtain a permit from the federal government before they can begin operations. CEPA also sets out requirements for site selection and characterisation, monitoring and reporting, and financial assurance.

CCUS operations in the EU are regulated under the EU ETS and the Carbon Capture and Storage Directive (CCS Directive). The EU ETS puts a price on CO_2 emissions, which incentivises companies to reduce their emissions or invest in low-carbon technologies such as CCUS. The CCS Directive sets out requirements for CCS projects, including requirements for permitting, site selection and characterisation, monitoring and reporting, and financial assurance. Table 5 displays a list of best practices in CCUS regulatory frameworks.

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TABLE 5 CCUS regulatory frameworks: best practices

Category	Best practice	Example	References
Clear regulatory framework	Provide clear and concise guidance on permitting, operational standards and regulatory oversight.	The United States has a comprehensive regulatory framework led by the EPA, ensuring clarity in permitting and operational standards.	(EPA, 2021)
		The EU has established a regulatory framework that provides clarity on permitting, liability and long-term site management for CCUS projects.	(EC, 2020)
Risk assessment and management	Mandate comprehensive risk assessments for CCUS projects, covering hazard identification, prevention and response.	Canada's Alberta Energy Regulator mandates comprehensive risk assessments for CCUS projects, covering hazard identification, prevention and response.	(AER, 2021)
		Australia's Department of Industry, Science and Resources emphasises thorough risk assessments for CCUS, with a focus on risk management plans.	(DISER, 2021)
Site characterisation and selection	Enforce rigorous site characterisation requirements, including detailed geological assessments and public consultation.	The United Kingdom's Oil and Gas Authority (OGA) enforces rigorous site characterisation requirements for offshore storage projects, including detailed geological assessments.	(UK Oil and Gas Authority, 2021)
		Japan's Ministry of Economy, Trade and Industry (METI) emphasises the importance of public consultation in the site selection process for CCUS projects.	(METI, 2021)
Well design and integrity	Enforce strict well design and integrity standards, emphasising regular inspections and robust well construction.	Norway's Petroleum Safety Authority (PSA) enforces strict well design and integrity standards for offshore storage, emphasising regular inspections and robust well construction.	(Norway Petroleum Safety Authority, 2021)
		The Canadian CCUS regulatory framework includes well integrity requirements for both onshore and offshore projects to prevent leaks and ensure safe storage.	(Government of Canada, 2021)
Monitoring and verification	Mandate continuous monitoring and verification of injection sites to ensure CO_2 containment and to identify any potential leaks or anomalies.	Australia's regulations mandate continuous monitoring and verification of injection sites to ensure CO_2 containment and to identify any potential leaks or anomalies.	(DISER, 2021)
		Canada's regulations require operators to implement rigorous monitoring and reporting protocols to demonstrate the effectiveness of CCUS storage.	(AER, 2021)
Liability and closure provisions	Require operators to establish financial assurance mechanisms to cover potential liabilities related to site closure and post-injection monitoring.	In the Netherlands, the regulators requested a financial security figure large enough to cover all events, routine or unplanned, regardless of probability, for a notional monitoring period of 50 years.	(PBL, 2021)
		The United Kingdom's regulatory framework includes provisions for financial responsibility and liability in case of adverse events during CCUS operations or site closure.	(UK Oil and Gas Authority, 2021)

Regulatory flexibility and adaptability	Design CCUS regulatory frameworks to be adaptable and responsive to technological advancements and changing circumstances.	Norway's regulatory framework for CCUS, overseen by the PSA, is designed to be adaptable and responsive to technological advancements and changing circumstances. The PSA regularly reviews and updates regulations to align with the latest industry developments.	(Norway Petroleum Safety Authority, 2021)
		The United States continuously revises its CCUS regulations to accommodate emerging technologies. The DOE collaborates with industry stakeholders to assess and adjust regulatory frameworks as needed.	(DOE, 2020)
International collaboration	Promote international collaboration on CCUS regulations and projects to accelerate progress and reduce costs.	The Carbon Sequestration Leadership Forum (CSLF) is an international initiative comprising multiple countries, including Australia, China, and Japan, collaborating to advance CCUS technologies. Member countries work together to develop common regulatory practices and share experiences to enhance the global deployment of CCUS.	(CSLF, 2021)
		Several North Sea countries, such as the Netherlands, Norway, and the United Kingdom, collaborate through the North Sea Basin Task Force on CCUS regulations and projects. They share best practices, align regulations and co-ordinate research efforts to optimise CCUS deployment in the region.	(NSBT, 2021)
Technology neutrality	Avoid favouring specific CCUS technologies, allowing for innovation and market-driven selection of the most effective and cost-efficient technologies.	The United States' regulatory framework is technology neutral, allowing for the deployment of a variety of CCUS technologies.	(EPA, 2021)
Public engagement	Promote public engagement in CCUS project development and decision making to build trust and support.	Canada's regulatory framework requires public consultation during the site selection process for CCUS projects.	(AER, 2021)

These examples demonstrate best practices in CCUS regulatory frameworks, covering clarity, risk management, site assessment, well integrity, monitoring, liability provisions and more. Specific regulatory practices may vary by country, emphasising the importance of consulting regional or national regulatory authorities for up-to-date information.

3.4 Liability concepts and financial guarantees management

CCUS liability concepts and financial guarantees management are essential aspects of regulatory frameworks to ensure the safe and responsible operation of CCUS projects.

Liability concepts

- **Operator liability:** CCUS regulations typically designate the project operator as the party responsible for ensuring the safe and compliant operation of the facility. This includes liability for any accidents, leaks or damages that may occur during the project's life cycle.
- **Long-term liability:** CCUS projects often have long-term responsibilities, such as site monitoring, maintenance and liability for potential future issues even after the project ceases active operations. Clear regulatory provisions should define these long-term responsibilities.
- **Third-party liability:** Regulations should address third-party liability, outlining the operator's responsibility for potential harm to neighbouring communities, ecosystems or property. Adequate safeguards and financial provisions should be in place to cover such liabilities.

Financial guarantees management

- **Financial assurance requirements:** Regulatory authorities typically require CCUS project operators to demonstrate financial assurance mechanisms to cover potential liabilities (see Table 6). These mechanisms ensure that funds are available for addressing accidents, environmental remediation, site closure and long-term monitoring.
- **Calculation of financial guarantees:** Regulatory authorities determine the amount of financial guarantees based on risk assessments, project size, potential liabilities and site-specific factors. This calculation ensures that adequate funds are available to address any foreseeable issues.
- **Regular review and adjustment:** Financial guarantees should be subject to periodic review and adjustment to align with changing project circumstances, evolving risk profiles and regulatory updates.
- **Access and transparency:** Regulatory frameworks should define how regulatory authorities and affected stakeholders can access and verify the financial guarantees. Transparency is crucial to building trust in the management of financial provisions.

TABLE 6 Financial assurance mechanisms for CCUS projects

Category	Financial assurance mechanism	Example
Insurance policies	Liability insurance	A policy that provides financial protection in case of accidents, property damage or harm to third parties related to CCUS operations.
Financial instruments	Surety bonds	A financial instrument where a third party (the surety) guarantees the payment of a specified amount if the operator fails to meet its obligations.
Financial instruments	Letters of credit	A financial instrument from a financial institution ensuring that funds are available to cover any potential liabilities or obligations.
Financial instruments	Cash deposits	Funds set aside in dedicated accounts to serve as a financial guarantee.
Financial instruments	Trust funds or escrow accounts	Funds set aside in specifically designated accounts for CCUS-related liabilities.
Corporate financial assurance	Corporate guarantees	A guarantee by the parent company or a financially stable entity to cover the financial obligations of the CCUS project.
Self-insurance	Self-insurance funds	Internal funds set up by the operator to cover potential liabilities.
Pooling mechanisms	Risk pooling	A collective financial assurance mechanism created by operators in collaborative CCUS projects or initiatives.
Performance bonds	Performance bonds	Bonds that ensure that the project operator fulfils specific obligations and responsibilities, including site closure and remediation.
Environmental surety bonds	Environmental surety bonds	Bonds designed specifically for environmental protection and compliance, which may be required by regulatory authorities to cover potential environmental liabilities related to CCUS.
Re-insurance	Re-insurance policies	Policies obtained by insurance companies to cover the risks associated with insuring CCUS projects.

Country examples

In the United States, the EPA's Underground Injection Control (UIC) programme outlines financial responsibility requirements for Class VI wells used for geologic sequestration of CO_2. Operators must demonstrate financial assurance through mechanisms such as insurance, financial instruments and dedicated accounts (EPA, 2021).

The United Kingdom's regulatory framework for CCUS, overseen by the Oil and Gas Authority, includes provisions for financial responsibility and liability management. Operators must provide financial assurances and demonstrate their ability to cover potential liabilities (NSTA Authority, n.a.).

CCUS liability concepts and financial guarantees management are integral components of regulatory frameworks to ensure that CCUS projects operate safely, responsibly, and in compliance with environmental and safety standards. These provisions help protect the environment, communities and project stakeholders while enabling the development of CCS solutions.

3.5 Critical regulatory gaps and required actions

CCUS is a critical technology for mitigating greenhouse gas emissions and addressing climate change. However, regulatory gaps exist, and these need to be addressed to facilitate the widespread deployment of CCUS projects. Table 7 highlights some of the critical regulatory gaps and the required actions to close them.

TABLE 7 Regulatory and engagement gaps with corrective actions

Issue	Gap	Required action
Unclear liability and long-term responsibility	Ambiguity in defining long-term liability and responsibility for CCUS sites after project closure can deter investment and hinder project development.	Regulators should establish clear and comprehensive guidelines defining long-term liability and responsibilities, including monitoring, site closure and post-injection monitoring. Financial assurance mechanisms must also be defined to cover these long-term commitments.
Harmonisation of international standards	Lack of global harmonisation of CCUS standards and regulations can create challenges for international projects and hinder cross-border collaboration.	Collaboration between countries and international organisations (*e.g.* IEA, United Nations) should focus on harmonising CCUS standards, protocols and regulations to facilitate global co-operation and knowledge sharing.
Public perception and stakeholder engagement	Public awareness and understanding of CCUS projects are often limited, leading to concerns and opposition.	Implement robust public engagement and education programmes, led by both government and the private sector, to inform and involve communities in the decision-making process. Address concerns transparently and pro-actively to build trust.
Regulatory streamlining and expedited permitting	Cumbersome and lengthy permitting processes can delay CCUS project development and increase costs.	Regulators should streamline permitting processes for CCUS projects while ensuring that environmental and safety standards are met. Expedited permitting for projects with a low environmental impact should be considered.
Integration with existing infrastructure	Clear regulatory guidance on integrating CCUS with existing infrastructure, such as power plants or industrial facilities, is lacking.	Develop regulations that encourage the retrofitting of existing facilities with CCUS technology, addressing issues related to permitting, safety and liability.
Regulatory support for CO_2 utilisation	Regulations often focus primarily on CO_2 storage, with less attention given to CO_2 utilisation technologies.	Regulators should consider creating specific frameworks and incentives for CO_2 utilisation projects, such as CO_2-based product manufacturing.
Monitoring and verification standards	Lack of standardised monitoring and verification protocols can affect the credibility and effectiveness of CCUS projects.	Develop and implement standardised monitoring and verification guidelines, including data reporting and sharing requirements, to ensure transparency and accountability.
Risk mitigation strategies	Inadequate guidance on risk assessment and mitigation measures for CCUS projects can lead to uncertainty and reluctance among investors and operators.	Regulators should work with industry stakeholders to develop comprehensive risk assessment frameworks and promote the adoption of best practices in risk management.

Key barriers to the deployment of BECCS

1) **Lack of a holistic approach to innovation:** A key challenge is the lack of an integrated strategy to land use, which balances agriculture, energy production and ecosystem services. This gap hinders the sustainable management of land, particularly for greenhouse gas removal methods such as afforestation.

2) **Limited market demand for negative emissions:** Policies to stimulate market demand for BECCS and other greenhouse gas removal technologies are lacking. There are particularly weak incentives for carbon removal through BECCS and other engineered solutions.

3) **Lack of agility in the governance of new innovations:** Scaling up BECCS requires close monitoring, and governments must be prepared to pivot if outcomes do not align with required greenhouse gas reductions, or to withdraw support if it proves ineffective. Without clear mechanisms for flexibility, there is a risk of becoming locked in to ineffective or counterproductive solutions.

4) **Partially developed regulation of biomass supply chains:** These regulations aim to ensure sustainability and environmental integrity in sectors such as bioenergy and carbon capture but may still be evolving or incomplete due to the complexity of biomass supply chains (UCL, 2020).

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4 Methodologies and standards for MRV and certification of carbon credits

4.1 Background

Monitoring, reporting and verification (MRV) and certification of carbon credits are crucial in quantifying the net carbon reductions achieved through BECCS projects. These methodologies ensure that the CO_2 captured and stored via BECCS is accurately accounted for, thereby validating the environmental benefits and supporting the issuance of tradable carbon credits.

Addressing climate change will require precise measurement, transparent reporting, and rigorous verification of greenhouse gas emission reductions and CO_2 removal initiatives. Central to this mission are the methodologies and standards governing MRV practices and the certification of carbon credits. These methodologies and standards serve as the foundation on which the integrity and effectiveness of carbon markets and offset programmes are built.

Climate change mitigation and carbon credits: Climate change mitigation efforts require concerted global action to reduce greenhouse gas emissions and limit the rise in global temperatures. International agreements, such as the Kyoto Protocol and the Paris Agreement, have set emission reduction targets. Carbon credits, or offsets, are a market-based mechanism that incentivises emission reductions and removals. These credits are generated when projects effectively reduce or capture more emissions than they emit, and they can be traded or sold, playing a pivotal role in achieving climate goals (UNFCCC, 2021a).

MRV frameworks and methodologies: The MRV framework is the backbone of carbon credit programmes. It ensures that emission data are measured accurately, reported transparently and verified independently. MRV encompasses a wide array of activities, from quantifying emissions to documenting emission reduction projects. Methodologies underpin MRV processes by providing guidelines and procedures for quantifying emission reductions and removals. They establish a consistent and reliable basis for calculating carbon credits. Various methodologies cater to different types of projects, including afforestation and reforestation, renewable energy and industrial processes.

Carbon credit standards: Several organisations have developed rigorous standards for carbon credits to maintain their quality and environmental integrity. Notable standards include the Verified Carbon Standard (VCS), the Gold Standard and the Climate Action Reserve (CAR). These standards define stringent criteria for the creation, validation and verification of carbon credits.

Market mechanisms: Carbon credits are exchanged in both voluntary and compliance markets. Voluntary markets allow entities and individuals to offset their emissions voluntarily, while compliance markets, such as the EU ETS, impose emission reduction targets on regulated entities (EC, 2021).

Challenges and criticisms: The carbon credit market faces challenges related to the credibility of credits, the concept of additionality (proving that emission reductions would not have occurred without the project) and concerns about double counting. Criticisms extend to the efficacy of offsetting as a climate mitigation strategy.

Methodologies and standards governing MRV and carbon credit certification are pivotal to the credibility and accountability of carbon markets. They foster transparency, uphold the credibility of emission reduction projects, and address multi-faceted environmental, social and economic considerations associated with carbon offset initiatives.

4.2 Certification landscape: National (compliance) versus voluntary schemes

The certification of carbon credits plays a pivotal role in validating and verifying emission reduction and removal initiatives to combat climate change. These certifications are essential for building trust, ensuring transparency and promoting the credibility of carbon markets. Within the certification landscape, two primary categories exist: national and voluntary schemes. Each has distinct characteristics and serves unique purposes in advancing global climate goals. Table 8 provides examples of illustrative CCUS certification mechanisms.

National (compliance) certification schemes

1) **Definition and purpose:** National certification schemes are established by governments or regulatory bodies within a specific country or region. Their primary purpose is to regulate and oversee carbon credit programmes in compliance with national or regional emission reduction targets and regulations (EC, 2018).
2) **Regulatory framework:** These schemes operate under a legal and regulatory framework determined by the respective government. They are often mandatory for entities subject to emission reduction obligations, such as those participating in emissions trading systems (ETSs) or complying with national climate policies (EC, 2021).
3) **Verification and reporting:** National certification schemes mandate rigorous verification and reporting processes to ensure that emission reductions meet required standards. Independent third-party auditors are commonly employed to verify emissions data and assess compliance (DOE, 2021).
4) **Credibility and compliance:** Compliance with national or regional regulations is a central focus, ensuring that certified credits are recognised and accepted for meeting emission reduction obligations (DOE, 2021). These schemes contribute to achieving country-specific emission reduction targets set forth in international agreements (UNFCCC, 2021b).

Voluntary certification schemes

1) **Definition and purpose:** Voluntary certification schemes are market-driven initiatives designed to meet the demand for carbon credits from entities or individuals voluntarily seeking to offset their emissions (Verified Carbon Standard, 2021). They operate independently of government mandates and regulatory obligations.
2) **Market driven:** Voluntary schemes cater to a diverse range of entities, including corporations, organisations and individuals looking to take pro-active steps towards environmental responsibility (Verra, 2021). Market demand and consumer preferences influence the use of voluntary credits.
3) **Additional sustainability criteria:** Voluntary certification often includes broader sustainability criteria beyond emission reductions, addressing co-benefits such as social and environmental impacts (Gold Standard, 2021). These schemes align with corporate sustainability goals and stakeholder expectations.
4) **Transparency and credibility:** Voluntary schemes prioritise transparency and credibility through standardised methodologies, independent verification and public reporting of project details (Verified Carbon Standard, 2021). They promote the voluntary market's integrity and public trust.

The scope and coverage of certification mechanisms, whether public or private, are essential in ensuring the credibility and environmental integrity of carbon credits and emission reduction projects. These mechanisms vary greatly based on their objectives, governance structures and the sectors they encompass. An overview of the scope and coverage of existing certification mechanisms is provided below, with examples from various sources and emissions sectors, along with references.

Public certification mechanisms

Public certification mechanisms typically have a comprehensive scope that covers a wide range of emissions sources and project types within a specific jurisdiction. For instance, the EU ETS encompasses emissions from sectors such as power generation, industrial processes, aviation and more. The coverage of public certification mechanisms is often mandatory for entities with emission reduction obligations under national or regional climate policies. In the EU ETS, regulated entities, including power plants, factories, and airlines, must comply with emissions caps and either reduce emissions or purchase carbon allowances (EC, 2021).

Private certification mechanisms

Private certification mechanisms operate on a global scale, allowing them to certify emission reduction projects across diverse sectors and geographies. The VCS, for example, certifies projects such as renewable energy installations, reforestation and afforestation efforts, energy efficiency initiatives and CCUS projects worldwide (Verified Carbon Standard, 2021). Private certification mechanisms cater to voluntary participants and a broad range of sectors. Corporations, organisations and individuals voluntarily engage with these mechanisms to offset their carbon emissions. For instance, companies can seek certification for emission reductions achieved through energy-efficient manufacturing processes, while individuals can offset their carbon footprint by supporting reforestation projects (Gold Standard, 2021).

TABLE 8 Illustrative CCUS certification mechanisms

Sector	Public mechanism	Private mechanism
Energy sector	The California Air Resources Board (CARB) oversees the certification of emission reductions in the energy sector through the California Cap-and-Trade Program.	The VCS certifies renewable energy projects globally, such as wind farms and solar installations.
Land use and forestry	Norway's International Climate and Forest Initiative certifies emission reductions from forest conservation and reforestation projects.	The Gold Standard certifies afforestation and reforestation projects with a focus on biodiversity and community engagement.
Industrial processes	The Australian Clean Energy Regulator certifies emission reductions in industrial processes under the Australian Emissions Reduction Fund.	The VCS certifies emission reductions in industrial sectors, including emissions capture and utilisation projects.
Aviation	The EU ETS includes aviation emissions, requiring airlines operating within the EU to comply with emissions caps and to offset excess emissions.	Airlines can voluntarily offset emissions through private certification mechanisms such as the VCS.

In summary, the scope and coverage of certification mechanisms are tailored to their specific objectives and regulatory frameworks. Public mechanisms are often jurisdiction-specific and tied to regulatory compliance, while private mechanisms operate globally and cater to voluntary participants. These mechanisms cover a wide array of sectors and emissions sources, contributing to emission reductions and the credibility of carbon markets.

4.3 Best practices in MRV and certification

Ensuring the accuracy, transparency and credibility of emission reduction projects and carbon credits requires adherence to best practices in MRV and certification (see Table 9). To this end, the IEA has published a CCUS handbook aiming to inform energy sector stakeholders about CO_2 storage resources and their development. The handbook provides an overview of geological storage and its benefits, risks and socio-economic considerations. It also contains a detailed MRV overview (IEA, 2022c). These practices, whether applied by public or private mechanisms, are essential for maintaining the integrity of carbon markets and demonstrating meaningful contributions to climate mitigation.

TABLE 9 Key best practices in MRV and certification

Key practices	Description	References
Standardised methodologies	Employ standardised methodologies for quantifying emission reductions and removals.	United Nations Framework Convention on Climate Change (UNFCCC, 2021a), Methodologies for the Reporting of Greenhouse Gas Emissions and Removals.
Rigorous data collection and analysis	Implement robust data collection and analysis procedures, ensuring the accuracy and completeness of emissions data.	European Commission (EC, 2018), EU ETS.
Transparent reporting	Maintain transparency by publicly reporting emissions data and project details.	Verified Carbon Standard (Verified Carbon Standard, 2021), VCS Program.
Additionality assessment	Conduct rigorous additionality assessments to demonstrate that emission reductions or removals would not have occurred without the project.	Gold Standard (Gold Standard, 2021), Gold Standard for the Global Goals.
Independent verification	Engage independent third-party auditors to verify emissions data and project compliance.	Verified Carbon Standard (Verified Carbon Standard, 2021) VCS Program.
Co-benefits assessment	Evaluate and report on co-benefits associated with emission reduction projects, such as improvements in air quality, biodiversity conservation and socio-economic development.	Gold Standard (Gold Standard, 2021), Gold Standard for the Global Goals.
Continual monitoring and reporting	Implement ongoing monitoring and reporting of emission reductions, even after certification.	European Commission (EC, 2018), EU ETS.
Public engagement and stakeholder consultation	Engage with local communities and stakeholders in project areas. Public consultation and engagement can help address concerns, ensure project acceptance, and enhance social and environmental co-benefits.	Gold Standard (Gold Standard, 2021), Gold Standard for the Global Goals.
Continuous improvement	Embrace a culture of continuous improvement by regularly reviewing and updating methodologies and practices.	United Nations Framework Convention on Climate Change (UNFCCC, 2021a), Methodologies for the Reporting of Greenhouse Gas Emissions and Removals.

By adhering to these best practices in MRV and certification, carbon credit programmes and emission reduction projects can maintain credibility, transparency and effectiveness in contributing to global climate change mitigation efforts.

4.4 Carbon trading systems and their implications for CCUS

Carbon trading systems, also known as ETS, are market-based mechanisms designed to reduce greenhouse gas emissions and combat climate change. These systems assign a financial value to emissions and create a market for trading carbon credits. They can have significant implications for CCUS initiatives (see Table 10).

How carbon trading systems work

1) **Cap-and-trade mechanism:** Carbon trading systems operate on a cap-and-trade mechanism. Governments or regulatory authorities set a cap on the total allowable greenhouse gas emissions within a specific jurisdiction or sector.
2) **Emission allowances:** Emission allowances, representing the right to emit a certain amount of greenhouse gas emissions, are distributed or auctioned to regulated entities, such as power plants, factories and airlines.
3) **Market for carbon credits:** Regulated entities must hold enough allowances to cover their emissions. If they exceed their allocated allowances, they can purchase additional allowances or carbon credits from the carbon market.
4) **Carbon credits:** Carbon credits are units representing emission reductions or removals achieved by CCUS projects, renewable energy or other carbon mitigation efforts. Entities that reduce emissions below their allocated allowances can generate carbon credits, which they can sell to those exceeding their allowances.
5) **Trading:** A secondary market for buying and selling carbon allowances and credits is established. This market enables entities to trade emissions rights, providing economic incentives for emission reduction.

TABLE 10 Carbon trading systems: implications for CCUS

Key points	Details
Incentives for CCUS	Carbon trading systems create financial incentives for CCUS projects. Entities that struggle to meet emissions targets can offset their excess emissions by purchasing carbon credits generated by CCUS initiatives.
Additional revenue stream	CCUS projects can generate revenue by selling carbon credits in the carbon market. This additional revenue stream can enhance the economic viability of CCUS ventures.
Accelerated CCUS deployment	Carbon trading systems can expedite the deployment of CCUS technologies, as they offer a clear economic advantage to entities seeking compliance with emission reduction targets.
Integration into climate policies	CCUS becomes an integral part of climate policies within carbon trading systems, contributing to overall emission reduction goals.
Monitoring and verification	Robust MRV processes are essential for ensuring the validity of carbon credits generated by CCUS projects. Accurate measurement and reporting are crucial for the successful participation of CCUS initiatives in carbon markets.
Complexity and challenges	The design and implementation of carbon trading systems can be complex. Determining the appropriate allocation of allowances, setting emission reduction targets and preventing market manipulation are ongoing challenges.
Complementary measures	While carbon trading systems are valuable tools, they are often most effective when complemented by other policy measures, such as regulatory standards, research and development support, and incentives for innovation in CCUS technologies.

Carbon trading systems have the potential to drive emission reductions and stimulate the development of CCUS technologies. However, their effectiveness depends on careful design, robust monitoring and strong enforcement to ensure that CCUS projects contribute meaningfully to global climate change mitigation efforts.

4.5 Critical gaps in certification processes

Addressing the existing critical gaps in certification processes (see Table 11) is essential to enhance the effectiveness and credibility of carbon certification processes and to achieve meaningful contributions to global climate goals.

TABLE 11 Certification processes: Critical gaps

Key points	Details
Verification challenges	Ensuring the accuracy and integrity of emissions data and robust verification mechanisms are essential to confirm the validity of emission reductions.
Additionality assessment	Determining additionality, *i.e.* whether emission reductions or removals are genuinely beyond business-as-usual, poses challenges in certification. Standardised methodologies for additionality assessment are needed.
MRV standardisation	Lack of standardised MRV processes across jurisdictions and sectors hinders consistency and comparability of carbon credits.
Co-benefits evaluation	Certification processes often do not comprehensively evaluate social and environmental co-benefits associated with emission reduction projects, leaving a gap in holistic sustainability assessments.
Baseline setting	Establishing accurate baselines against which emission reductions are measured can be challenging, especially in sectors with rapidly changing emissions profiles.
Double counting	Preventing double counting of emission reductions or removals across multiple certification schemes or initiatives remains a significant gap in the carbon market.
Lack of global governance	The absence of a global governing body for carbon certification results in varying standards and practices, making it challenging to harmonise certification processes.
Public awareness	Limited public awareness of certification schemes and their importance creates a gap in public understanding of the role of carbon credits in climate mitigation.
Financial accessibility	Small-scale emission reduction projects often lack access to the certification process due to high costs, creating inequities in participation.
Technology gaps	Emerging carbon removal technologies, such as direct air capture, lack established certification methodologies, creating a gap in their integration into carbon markets.
Market integrity	Gaps in preventing fraud, manipulation and misrepresentation within carbon markets challenge market integrity and trust.
Policy and regulatory uncertainty	Evolving climate policies and regulations can create uncertainty in certification processes, impacting project planning and investment decisions.
Carbon leakage	Addressing carbon leakage – where emission reductions in one area lead to increased emissions elsewhere – remains a complex challenge in certification.
Inclusivity	Ensuring inclusivity and participation of all regions and sectors in certification processes is a gap that needs to be addressed for equitable climate action.
Data security and privacy	With increasing reliance on digital data in certification, ensuring data security and privacy is a growing concern.

4.6 Accounting for BECCS as a negative emission technology

Accounting for BECCS as a negative emission technology requires quantifying the net reduction in atmospheric CO_2 resulting from the deployment of BECCS projects. This accounting approach considers the CO_2 removed from the atmosphere through the growth of biomass feedstocks, the capture of CO_2 emissions from bioenergy production, and the subsequent storage of captured CO_2 underground. The requirement for CO_2 storage accounting and verification follows a similar approach to regular CCUS requirements. By subtracting the emissions associated with biomass production, processing, and transport, the net amount of CO_2 removed from the atmosphere by BECCS can be determined. This net removal is then quantified and reported as negative emissions, representing a reduction in the overall greenhouse gas emissions contributing to climate change.

The challenges of accounting for negative CO_2 emissions are evident when attempting to integrate such emissions into project-based mechanisms such as the Clean Development Mechanism (CDM) and various emissions trading systems. While some schemes and mechanisms are capable of accounting for negative emissions or could be adapted to do so, others lack this capability. The accounting complexity depends on factors such as the treatment of sinks like forests and land use and the treatment of CCS in explicit or implicit terms. BECCS presents difficulties in regional cap-and-trade emission schemes, as biomass energy is typically included in the scheme's baseline or because biomass entities are excluded. Project-based schemes such as the CDM are more conducive to recognising negative emissions. Generally, negative emissions can be accounted for as "credits" or as "net-back", wherein removed CO_2 can be subtracted from positive emissions from other sources in a broad portfolio of emission sources (Torvanger, 2018).

Accounting for net CO_2 emissions from BECCS deployment can be broken down into six components: biomass growth, carbon cycle interaction, biomass feedstock processing, energy conversion, CO_2 capture and CO_2 storage. While biomass growth and interaction with the carbon cycle would typically be accounted for under land use, the remaining components fall under the energy sector. The net removal of CO_2 achieved through BECCS relies on all six components described in Table 12. The complexities associated with these components highlight the need for a unified accounting framework for BECCS as a negative emission technology at the international level to facilitate its further development.

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TABLE 12 BECCS components and accounting of net negative emissions

BECCS component	Description	Requirements
Biomass growth	CO_2 capture in biomass through photosynthesis. Account for delayed regrowth.	Standardised framework for sustainable biomass production and harvesting management and accounting. Trade-offs with other area uses.
Biomass transport and processing	Account CO_2 emissions from harvesting, transport, and processing of biomass for energy. Life cycle perspective. Delivery chain effects. Indirect e ects (from price changes and other effects).	Standardised accounting of the steps required from producing biomass until preparing for combustion or processing, implying CO_2 emissions. Decide on boundaries for life cycle, delivery chain, and indirect effects accounting.
Interaction with carbon cycle	Global carbon cycle dynamics reduce net CO_2 removal.	Standardised accounting framework.
Biomass combustion; Industrial processes	Production of heat and/or power from biomass, synthetic natural gas or hydrogen.	Standardised accounting of biomass carbon to energy, and CO_2 transformation efficiency.
CCS: CO_2 capture	Efficiency of CO_2 capture from exhaust is less than 100%.	Decide on standardised CO_2 capture efficiency from combustion, possibly dependent on capture technology.
CCS: CO_2 transport and storage	Transportation by pipelines or ships. Safe storage in geological formations.	Identify candidates for geological storage sites. Verify suitability according to regulations. Performance monitoring. Contingency plans in case of CO_2 leakage.
Net CO_2 removal	Sum of negative and positive CO_2 emission components.	The BECCS framework determines net CO_2 removal, which is basis for rewarding.

Source: (Torvanger, 2018).

5 The role of bioenergy and BECCUS

Bioenergy can play an essential role in meeting the 1.5°C climate target due to its ability to replace fossil fuels across various energy sectors. These sectors include electricity, industry, buildings, transport and chemical feedstocks (IRENA, 2023).

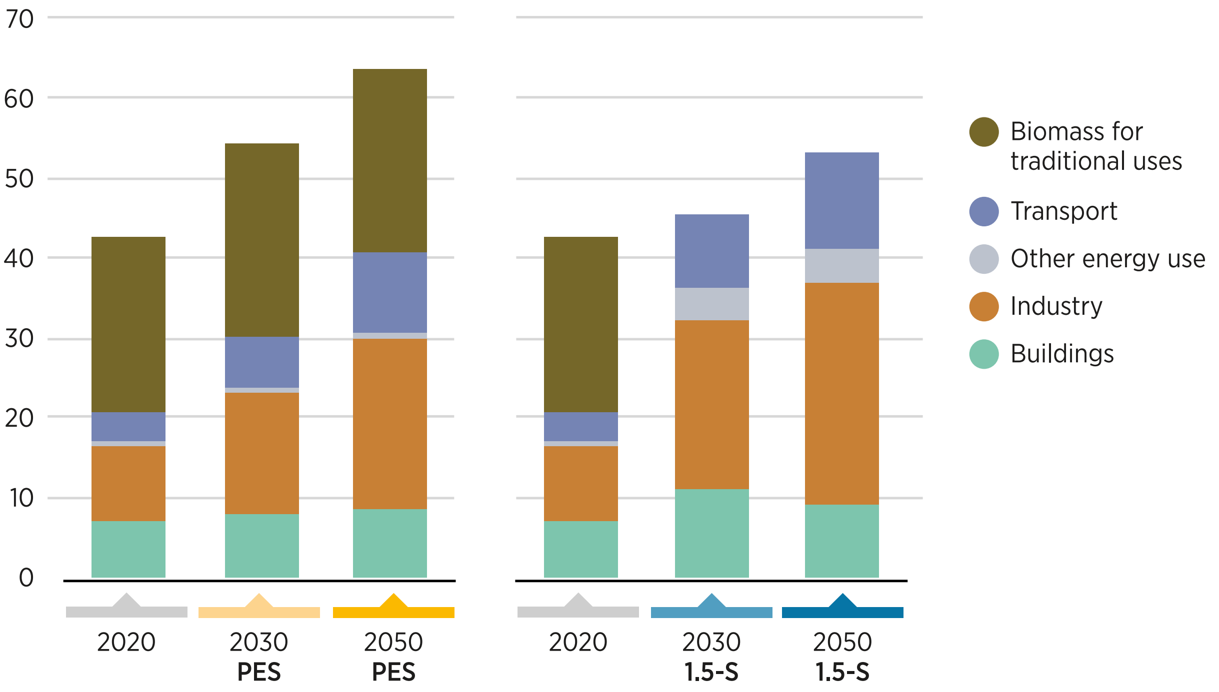
Integrated with CCUS, bioenergy can be a player in the shift towards sustainable energy, playing a pivotal role in achieving negative emissions. As mentioned in section 1, BECCUS can help meet global and national climate targets. However, it is crucial to enhance the sustainability guidelines and regulations that govern the entire biomass supply chain to ensure that biomass sourcing truly supports sustainable energy goals.

5.1 Bioenergy supply and consumption

In 2020, bioenergy contributed 9.5% to the total primary energy supply: 43% from modern solid biomass, 39% from traditional uses in developing countries, and 18% from biogas and biofuels.

According to IRENA's 1.5°C Scenario, bioenergy's contribution to the primary energy supply will need to quadruple by 2050 compared to 2020 levels. By 2050, it will need to account for 22% of the primary energy supply. During this period and in this scenario, the use of modern bioenergy in total final energy consumption would also rise to 15% globally. As shown in Figure 1, the industry sector will be the largest consumer, using 52% of this energy, followed by transport at 23%, buildings at 18%, and other sectors making up the remaining 8% (IRENA, 2023).

FIGURE 1 Bioenergy final energy consumption by sector in 2020, 2030 and 2050 under the Planned Energy Scenario and the 1.5°C Scenario



Source: (IRENA, 2023).

Note: EJ = exajoule; PES = Planned Energy Scenario; 1.5-S = 1.5°C Scenario.

The volume and proportion of bioenergy are expected to increase substantially. Over the next few decades, the need for forest biomass is projected to rise as governments and owners of power sector assets seek to transition from coal while maintaining existing infrastructure (Reid *et al.*, 2019).

To ensure a sustainable supply of bioenergy, it is essential to pursue both energy production and sustainable development. Prioritising advanced feedstocks, such as agricultural residues, can help avoid land-use conflicts. Moreover, sustainable practices are crucial to ensuring that bioenergy production does not expand cropland use or threaten biodiversity. Integrating bioenergy with agriculture is key to maintaining both food security and environmental conservation (IEA, 2023b).

Ensuring the sustainability of bioenergy requires careful management of the entire supply chain, from biomass production to transport and conversion processes. It is essential to analyse life-cycle emissions and the energy balance to confirm that bioenergy contributes positively to carbon mitigation. Aligning supply and demand with sustainable practices means producing bioenergy to meet rising demand without compromising environmental and social standards. This involves using traceable and responsibly sourced biomass feedstocks, which promotes biodiversity preservation and reduces greenhouse gas emissions throughout the supply chain.

Comprehensive policy support and strategic co-ordination are crucial for sustainable bioenergy development, necessitating a detailed understanding of the supply chain from biomass feedstock production to end-use applications to ensure that all processes contribute to sustainability and climate goals (IRENA, 2022).

5.2 Biomass supply chain

Biomass supply chains are complex systems with several interdependencies. They underpin both traditional and innovative bioproducts through common elements such as crop development, sustainable management, harvesting, various transport modes, storage and pre-processing. These elements are integral to producing a wide array of outputs such as fuels, materials and chemicals. The system is dynamic, with feedback loops meaning that any change in one area can influence others, potentially affecting the entire production and market landscape (USDA, 2024).

Designing a sustainable and green biomass supply chain (BSC) is essential for effectively commercialising bioenergy. Integrating environmental, economic and socio-cultural aspects into BSC models is crucial to achieving sustainability and the United Nations Sustainable Development Goals (SDGs). Advanced technologies such as artificial intelligence (AI), unmanned aerial vehicles (UAVs) and geographic information systems (GIS) can support these efforts by enhancing efficiency. However, the fundamental challenges of economic, technological and policy barriers must be addressed through a holistic approach to ensure the sustainable deployment of bioenergy (Hiloidhari *et al.*, 2023).

This holistic approach extends into BECCS, where a critical review of life-cycle assessments (LCAs) reveals the potential for achieving negative emissions. The variability in net negative life-cycle emissions from BECCS arises from differences in technology, LCA methodology and underlying assumptions. Addressing these variations requires standardised guidelines for BECCS LCA and considering the comprehensive environmental impacts of BECCS, ensuring that all dimensions of sustainability are integrated into the broader biomass supply chain strategy (Wang *et al.*, 2024).

Key policy recommendations for the biomass supply chain

Addressing economic, technological and policy challenges is crucial for the deployment of bioenergy. Both reviews call for standardised methods and holistic approaches to overcome these barriers.

Biomass supply chain systems have a broad range of vulnerabilities, including biological, environmental, economic, geopolitical, and social challenges, as summarised in Table 13.

TABLE 13 Biomass supply systems challenges

Biomass supply systems challenges	
• Economic viability	• Education and outreach
• Climate change	• Infrastructure
• Environmental sustainability	• Workforce
• Environmental justice	• Policy uncertainty
• Food security	• Geopolitics and trade risks
• Feedstock variability	• Limited domestic production

Source: (USDA, 2024).

Given the current vulnerabilities in biomass supply chains and the underdeveloped regulatory frameworks for these supply chains, the following recommendations are proposed to enhance governance and effectiveness (IRENA, 2022; USDA, 2024).

1) **Policy and regulatory measures:**
   a. Develop policies that integrate bioenergy with national energy strategies and sustainable development goals.
   b. Enforce standards and certifications to ensure that biomass is sustainably sourced, focusing on land use, biodiversity and emission reduction.
2) **Financial and fiscal incentives:**
   a. Provide subsidies, tax benefits and grants to support sustainable biomass practices and infrastructure development.
3) **Capacity building and public awareness:**
   a. Enhance educational programmes for sustainable biomass production, processing and logistics.
4) **Support for modern bioenergy technologies:**
   a. Promote advanced technologies in biomass supply chains to minimise environmental footprints and boost economic efficiency. Focus on advanced methods for harvesting, processing and transporting biomass.
5) **Effective policies and programmes** are essential for building capacity and developing markets in biomass supply chains globally. Promoting bio-based products through public procurement and voluntary labelling enhances market visibility. The biofuel market is influenced by government initiatives, including mandates for biofuels, low-carbon standards and production credits. Expanding these initiatives and introducing new ones could boost the market share of biofuels.
6) **Investing in infrastructure and workforce** development is crucial for a resilient biomass supply chain. Infrastructure investments and efficient transport systems are fundamental. Programmes that foster co-operatives and link manufacturers with feedstock producers ensure reliable supplies. Promoting climate-smart production practices enhances sustainability and resilience, supporting robust biomass supply chains aligned with climate and economic goals.

Implementing the recommended policies and focusing on key elements of biomass supply chains effectively supports the development of sustainable bioenergy. This strategic approach plays a significant role in advancing the global energy transition (IRENA, 2022).

5.3 Bioenergy policy framework

To maximise the environmental, social, and economic advantages of bioenergy, countries should establish regulations and certifications and foster partnerships to sustain the sustainability of biomass feedstock and the entire supply chain. Additionally, the deployment of bioenergy should be tailored to the local context and integrated with strategies from other sectors (IRENA, 2023).

Given the complexity and context-specific nature of bioenergy sustainability, a robust policy framework is essential to ensure that bioenergy contributes effectively to achieving the 1.5°C target. This framework should encompass the following (IEA, 2024b; IRENA, 2022) (see also Figure 2):

1) Sustainability-based target setting and long-term planning (bioenergy for the transition).
2) Cross-sector co-ordination, and sustainability governance through regulations and certification schemes.
3) Integrating bioenergy policy with the Sustainable Development Goals (SDGs), which is crucial for comprehensive and cohesive policy making.
4) Blending mandates, renewable fuel standards, and certifications, which are essential to support bioenergy's role in the transition.
5) Incentives such as loan guarantees, financial and fiscal incentives.
6) Development of policies that encourage the use of bioenergy to lower emissions, while acknowledging its advantages and limitations in policy formulation.
7) Policies that integrate energy recovery from waste into waste management strategies and promote the use of waste and residue feedstocks for producing liquid biofuels. Additionally, policies should maximise the synergies and co-benefits of bioenergy generation, such as combining with waste management and providing interim solutions to decarbonise existing coal power plants before decommissioning.

FIGURE 2 A policy framework for sustainable bioenergy development

Source: (IRENA, 2022).

Note: SDG = sustainable development goal.

5.4 Integration of bioenergy with CCS and CCUS in policy frameworks

Policy frameworks for BECCUS must navigate the complexities of incentivising bioenergy while ensuring sustainable biomass sourcing and addressing potential competition with food production and biodiversity.

In summary, the relationship between bioenergy and BECCUS within policy frameworks is essential for their market development. By tackling the technical, financial, and regulatory challenges, policies can establish an ecosystem where bioenergy and BECCUS not only co-exist but also reinforce each other. This synergy fosters innovation, drives market growth and enhances contributions to climate change mitigation.

Additionally, it is equally crucial to develop comprehensive policies that encompass the entire supply chain, from biomass production to carbon capture and storage. Standardised guidelines and a focused consideration of environmental impacts are vital for the successful deployment of BECCUS. This integrated approach ensures that sustainability is thoroughly addressed across all stages, maximising the potential of BECCUS to meet climate objectives (Bellamy *et al.*, 2019).

The extensive use of biomass for CO_2 removal brings up significant environmental and social concerns, including an increased demand for freshwater, land competition, potential biodiversity loss and impacts on food security. Moreover, the carbon effects of substituting biomass for fossil fuels, influenced by feedstock choice, are also debated.

In response to these challenges, the following policy measures and technology insights are recommended to ensure the sustainable development of bioenergy via CCS and broader CCUS applications (Bellamy *et al.*, 2019; IEA, 2023c):

1) **Comprehensive policies:** Develop robust policies that encompass the entire BECCS supply chain, from biomass production to carbon capture and storage. This includes integrating BECCS into broader energy and climate policies for cohesive and effective implementation.

2) **Standardised guidelines**: Establish standardised guidelines for the life-cycle assessment (LCA) of BECCS to address variability in technology, methodology and assumptions. Focusing on broader environmental impacts beyond just carbon mitigation ensures the overall sustainability of BECCS.

3) **Flexible bioenergy and BECCS** are pivotal technologies for mitigating climate change. Flexible bioenergy allows for the adjustment of energy outputs (such as heat and electricity) to meet demand and can utilise various biomass feedstocks.

4) **The integration of CCS and CCU with flexible bioenergy** operations is technically feasible but requires a balance between operational flexibility and the efficiency of CO_2 capture. Business models for these technologies are influenced by market prices, regulatory frameworks and the availability of incentives for carbon capture and flexibility.

5) **The deployment of BECCUS varies greatly across different sectors**, such as electricity generation, industrial heat production and heavy industries like cement manufacturing. Each sector requires tailored policy approaches that address specific technological, economic and regulatory conditions.

6) **To fully understand the impacts of flexible BECCUS on the energy system, comprehensive energy system modelling is essential.** This approach will inform energy system modellers and policy makers about potential trade-offs that may arise when bioenergy installations simultaneously offer operational flexibility and CCS/U.

These recommendations aim to create a sustainable and integrated framework for bioenergy via BECCS and broader CCUS applications, ensuring that these technologies contribute effectively to global climate goals without compromising environmental and social aspects.

6 Conclusions and recommendations

6.1 CCUS policies

Effective bioenergy with CCUS policies is an essential element of global emission reduction targets. Governments worldwide are recognising the potential of bioenergy with CCUS in mitigating climate change, as evidenced by their commitments, financial support and innovative policy frameworks. However, addressing critical gaps and fostering international collaboration remain imperative to realising the full potential of BECCUS technologies. By continuously refining policies and embracing best practices, the global community can accelerate the adoption of CCUS and drive the transition to a sustainable, low-carbon future.

While significant progress has been made in BECCUS policy development, several areas require the attention of policy makers:

- **Policy consistency:** Robust policies need to be developed that encompass the entire BECCUS supply chain, from biomass production to carbon capture and storage. Some regions lack consistent CCUS policies, which hinders long-term investments. Addressing this gap requires sustained government commitment and bi-partisan support.
- **International collaboration:** CCUS projects often cross national borders. Establishing international agreements and harmonising regulations can streamline cross-border CCUS initiatives. The ability to move CO_2 across borders is essential for creating access to a diverse portfolio of potential storage sites worldwide, enabling economies of scale, and reducing individual project risks across regions.
- **Infrastructure investment:** Developing CO_2 transport and storage infrastructure requires substantial investments. Governments can play a crucial role by providing financial incentives and reducing the financial risks associated with such projects.
- **Co-ordinating clusters and common infrastructure:** A separate commercial framework for CO_2 transport and storage can enable shared infrastructure and economies of scale – but this also brings challenges for co-ordination and expansion.
- **Public perception:** Addressing public concerns about the safety and environmental impact of CCUS is essential. Governments should invest in public awareness campaigns to disseminate and share information about the benefits, costs and safety measures of CCUS.

6.2 CCUS regulations

Despite the significant progress that has been made in recent years, several critical regulatory gaps still need to be addressed to accelerate the deployment of CCUS technologies. These gaps include:

- **Lack of clarity and consistency in regulatory frameworks:** CCUS regulations vary widely from country to country, and even within countries. This lack of clarity and consistency can create uncertainty for investors and developers and make it difficult to finance and implement CCUS projects.
- **Complex and burdensome permitting processes:** Obtaining permits for CCUS projects can be a complex and time-consuming process, involving multiple agencies and levels of government. This can discourage investment and make it difficult to bring CCUS projects online quickly enough to meet climate goals.
- **Limited financial support:** CCUS technologies are still relatively new and expensive, and there is limited financial support available to support their development and deployment. This lack of financial support can make it difficult for CCUS projects to compete with other low-carbon technologies.
- **Public awareness and acceptance:** Public awareness and acceptance of CCUS is still relatively low. This lack of awareness and acceptance can create challenges for CCUS projects, such as opposition from local communities.

To address these critical regulatory gaps and accelerate the deployment of CCUS technologies, governments and other stakeholders are advised to take the following actions:

- **Develop clear and consistent regulatory frameworks:** Governments need to develop clear and consistent regulatory frameworks for CCUS that promote investment and deployment. These frameworks should be based on sound science and risk assessment and should be designed to be flexible and adaptable to technological advancements and changing circumstances.
- **Simplify and streamline permitting processes:** Governments need to simplify and streamline permitting processes for CCUS projects. This can be done by reducing the number of agencies involved in the permitting process, clarifying requirements, and providing greater certainty to investors and developers.
- **Provide financial support for CCUS projects:** Governments need to provide financial support for CCUS projects, such as through grants, loans and tax breaks. This support will help to reduce the risk of investment and make CCUS projects more competitive.
- **Promote international collaboration on CCUS regulations and projects:** This collaboration can help to accelerate the development and deployment of CCUS technologies by facilitating the sharing of best practices and lessons learnt.

6.3 Methodologies and standards for MRV and certification of carbon credits

The effectiveness of CCS implementation relies heavily on robust certification and trading processes that ensure the integrity and transparency of carbon credit mechanisms. Recommendations for carbon certification and trading processes related to CCS, aimed at addressing key challenges and fostering a more inclusive and secure framework for sustainable climate action, include:

- **Standardisation and governance:** Establish a global governing body to standardise MRV processes, ensuring uniformity and consistency in CCS certification.
- **Inclusive participation:** Reduce financial barriers for small-scale projects and encourage the participation of all regions and sectors to ensure equitable access to CCS certification.
- **Technological integration:** Develop specific methodologies and certification standards for the different carbon capture and removal technologies, such as direct air capture, to facilitate their integration into the carbon trading framework.
- **Data integrity and security:** Strengthen data security measures to prevent fraud and unauthorised access, ensuring the integrity and trustworthiness of the CCS trading process.

In addition to these conclusions and recommendations, there is a need for global collaboration to craft and implement customised policies and streamlined regulations. These regulations should be designed with the conditions and circumstances of developing countries and emerging economies in mind, to promote the seamless integration of CCUS technologies into national climate strategies.

Moreover, establishing financial mechanisms – including targeted incentives and collaborations with international institutions – to attract private investments and fund CCUS projects in developing countries will ensure sustainable and equitable development in these countries.

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