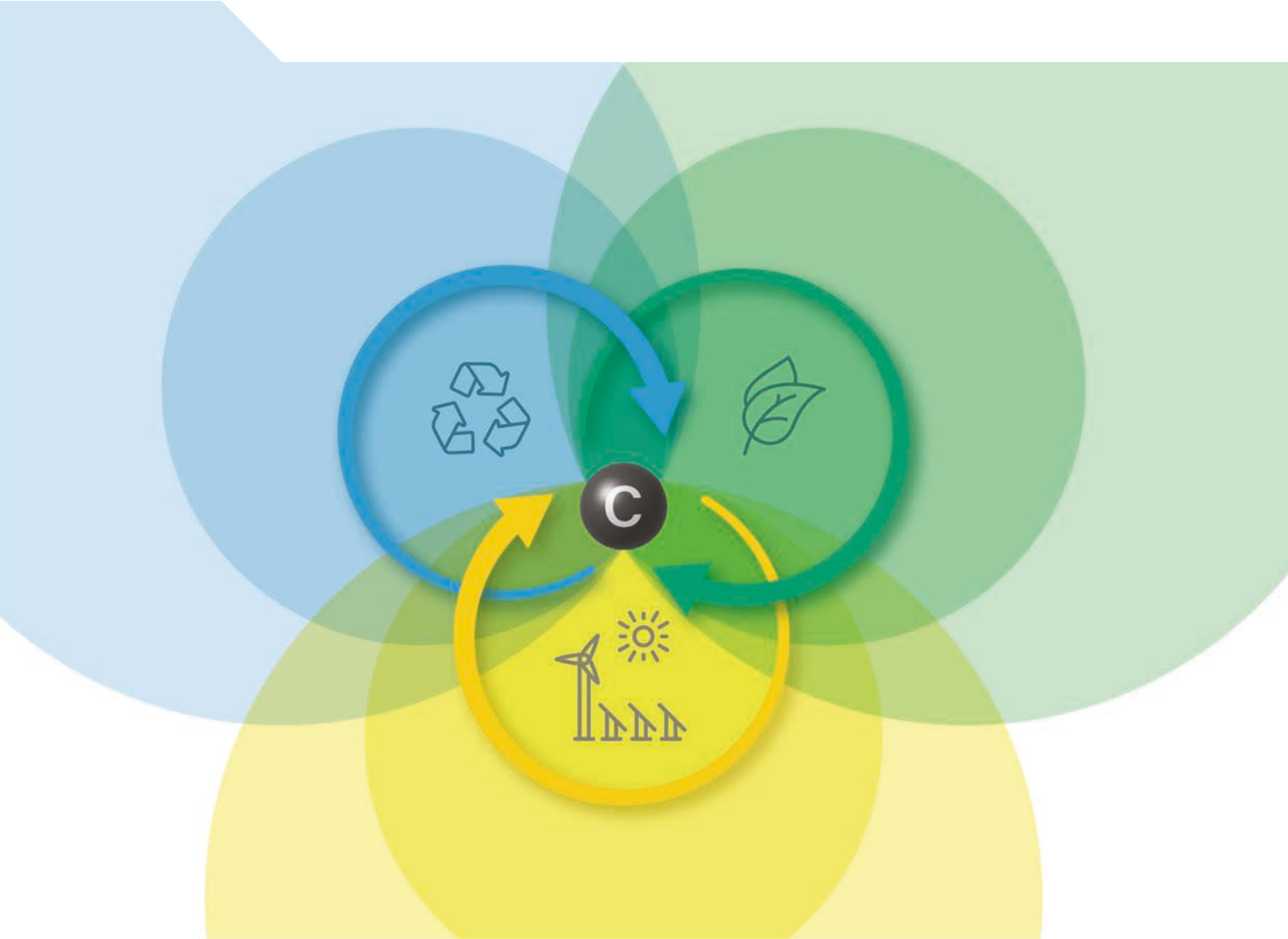
Carbon Management: Bioeconomy and Beyond



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Carbon Management: Bioeconomy and Beyond

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Foreword

The bioeconomy brings opportunities for economic growth while tackling climate change. Fossil carbon resources can be replaced by bio-based carbon resources, especially biomass. To allow these solutions to be scaled up without threats to biodiversity and the environment, it is necessary to develop the bioeconomy as a circular economy. With this carbon management approach, other sources of carbon complement biomass: industrial waste, including gases such as CO and CO_2, as well as physically and chemically recycled carbon. In the future, direct air capture (DAC) may become competitive and form part of the solution. These approaches can be considered 'circular' because they close material loops and keep carbon recycling in the economy rather than emitting carbon to the atmosphere. This report reviews a number of hybrid technologies that can be deployed to 'defossilise' economic sectors and sets out policy options to bring these technologies to commercial scale. In this case 'hybrid' refers to a combination of different types of technologies that can achieve a goal where a single technology cannot.

The report is not primarily about climate change and its mitigation. Whilst this is inherent to the report, much of what is discussed refers to other sustainability issues that will need to be addressed as well as reductions in greenhouse gas emissions. In particular, many of the described technologies have important roles in the relief of pressure on land. While biomass has important roles to play in a green transition, the use of waste materials such as industrial gases in technologies complements the use of biomass and widens the prospects for reaching net-zero carbon by mid-century. In doing so, other critical concerns of sustainability are addressed, such as preserving biodiversity and soil quality.

For policy makers, the future technological landscape generates one of the big challenges for the first half of this century. Much of the technology required is under-developed. A great deal of focus has been on carbon capture and storage (CCS). Whilst CCS is essential, the technologies described here are mostly for carbon capture and utilisation (CCU), which has the potential to write a new chapter in manufacturing. To do so requires government interventions across a large range of policy types. In general, there is a need for both supply-side and demand-side policies on a very large scale. The report points to policy efficiencies that would be availed by taking a holistic approach to policy to reduce the possibilities of unintended, and unwanted consequences created by policy dilemmas arising in this extremely complex arena.

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The cover image, designed by Brage Marvik of Lumar AS, aims to depict the dynamic interaction between available carbon resources – specifically bio-based carbon and recycled carbon – and the renewable energy necessary for carbon upgrading and recycling.

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- Carbon management policies webinars on “Global practices in sustainability indicators and assessment”, October 2020
- G20-OECD workshop: “Bioeconomy in the G20 and OECD countries: sharing and comparing the existing national strategies and policies for co-designing more effective Bioeconomy governance mechanisms and monitoring systems”, July 2021
- “Carbon management and policies towards 2050”, October 2021
- Ecomondo/OECD workshop: “Transition towards carbon neutrality”, November 2022

- OECD Green Growth & Sustainable Development Forum, “Green innovation and the impact of economic shocks”, Panel on: Innovation in bio-economy sectors for a circular economy GGSD event, November 2022
- Inputs from the IEA/Biofuture Platform on its work leading up to the Green Energy Ministerial, September 2022.

Sixteen case studies were received and are summarised in Chapter 5.

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Abbreviations and acronyms

AFOLU	Agriculture, forestry and other land use
BECCS	Bioenergy with Carbon Capture and Storage
BTX	Benzene, Toluene, Xylene
CAP	Common Agricultural Policy
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CDR	Carbon Dioxide Removal
CLT	Cross-Laminated Timber
COP	Conference of the Parties
CPI	Centre for Process Innovation
DAC	Direct Air Capture
ERDF	European Regional Development Fund
ETS	Emission Trading Systems
EU	European Union
FAO	Food and Agriculture Organization
FARC	Framework Act on Resource Circulation
GERD	Gross Domestic Expenditure on Research and Development
GHG	Greenhouse gase
GLT	Glue-Laminated Timber
GRI	Global Reporting Initiative
IEA	International Energy Agency
ISCC	International Sustainability and Carbon Certification system
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LPG	Liquefied Petroleum Gas
MOOC	Massive Open Online Courses
NAICS	North American Industrial Classification System
NZE	Net Zero Emissions
PyCCS	Pyrogenic Carbon Capture and Storage

R&D	Research and development
RSB	Roundtable on Sustainable Biomaterials
SAF	Sustainable Aviation Fuel
SCS	Sustainability Certification Schemes
SOC	Soil Organic Carbon
STI	Science, Technology and Innovation
STIP	Science, Technology and Innovation Policy
SSA	Smart Specialisation Areas
WTO	World Trade Organization

Executive summary

This report focuses on relieving pressures on land from agriculture and forestry by enlarging the bioeconomy to include alternative sources of bio-based carbon to complement biomass. In climate policy, most attention and resources has gone into energy and transportation, while much less attention has been given to industry. Yet, reaching net-zero greenhouse gas (GHG) emissions by 2050 requires the action of all countries and all sectors. The IPCC has warned that unless deep greenhouse gas (GHG) emissions cuts occur within the coming decades, limiting global warming to well below 2°C or 1.5°C, as stated in the Paris Agreement, will not be possible.

Energy and transportation can be decarbonised through electrification. Decarbonisation can also happen with hydrogen as a renewable energy carrier, one which can be stored more easily than electricity. For many industrial sectors, however, the term 'decarbonisation' can be misleading: industries such as plastics, cement and chemicals cannot do without carbon. In addition, aviation, maritime, and off-road transport have no immediate pathways to net-zero other than sustainable, carbon-based liquid fuels.

In this respect, 'defossilisation' would be a more appropriate term, which implies leaving fossil reserves in the ground and exploiting other sources of carbon. This mirrors the 'renewable carbon' concept which "*entails all carbon sources that avoid or substitute the use of any additional fossil carbon from the geosphere*". Renewable carbon can circulate between biosphere, atmosphere or technosphere, creating a circular carbon economy.

Main policy messages

Public policies that balance GHG reduction goals with other sustainability priorities can help meet the demand for sustainable carbon-based products

Carbon from sustainably grown biomass has an important role to play in meeting net-zero targets. However, this carbon source is insufficient to meet the likely demand for carbon-based fuels, chemicals and materials even in a highly electrified future. It is vital that all sustainable carbon sources including waste solids and gas are considered and appropriately incentivised.

Selection criteria should go beyond innovation excellence

Granting and public investment bodies need to judge the economic realism and impact potential of renewable carbon projects. Selection criteria have to go beyond excellence of science and engineering to include techno-economic assessments, technology maturity, social impact assessment and environmental credentials (not just GHG emissions reduction).

De-risk private investments in technology maturation

Many OECD countries' innovation strategies rely on private investments to complement public investments. This may be accomplished through public financial support to de-risk private investments in demonstration projects, including via novel public-private financing mechanisms.

Public policies can help building markets for renewable carbon

Public supply-side investments to build the new infrastructure are not enough if market conditions are not favourable. Competing with fossil-derived products is difficult in a world without full carbon pricing. Exemplar options for demand-side and regulatory policy include public procurement, production mandates, incentives, and setting new technical and business standards in the marketplace.

Innovation policies may benefit from sequencing

Innovation policies will be most effective if implemented in a logical order. A jumble of policies without direction and a progression path invites confusion. Hence, carbon management policies should be sequenced to optimise the effectiveness of each and all policy elements.

Policies can stimulate multi- and interdisciplinarity and hybrid technologies

Hybrid processes that involve multiple technologies can be more carbon, energy, and cost-efficient than single technologies. This complexity can be a challenge for government agencies responsible for grants and investments.

Technology deployment may benefit from industrial symbiosis

Industrial symbiosis can assume many functions, notably energy optimisation, reducing overall cost, and supporting the interplay between multiple applications of the same feedstock, reducing resource as well as business risk in the whole supply chain.

Policies should address opportunities across sectors

Because the driver of the policies supporting biofuels are similar to the driver for sustainable chemicals and materials, similar structures should apply to sustainable carbon resources regardless of end use sector. To achieve that, reliable calculations of GHG reductions for materials and chemicals are needed.

Complexity sets the scene for policy dilemmas and unintended consequences

For policy makers, the questions posed and the policy dilemmas are complicated and will inevitably result in compromises and trade-offs, and potentially unintended consequences.

Advancing climate and sustainability goals while maintaining a focus on living standards

Combining fossil fuel subsidy reform with a realistic carbon price, or consistent and well-designed incentives, are the ways to encourage investment in renewable carbon technologies. Meanwhile, in order to address potential social dilemmas, there is a need to include meaningful, deliberative public dialogue.

Holistic policy formulation and implementation

Without a holistic approach and understanding of the complex interactions of technologies, value chains, etc., innovation policies may fail. With this in mind, a holistic policy framework has been designed for this report. It may help policy makers construct a strategy connecting supply- and demand-side drivers, and sequence policy implementation. Specifically, this matrix may guide different ministries and agencies as to when and where they need to engage.

Case studies revealed hybrid technology approaches

This report reflects learning from a series of workshops and 16 case studies. Most of the case studies are not reliant on a single technology and typically illustrate the interplay of chemical and biotechnological solutions. This demonstrates the importance of a multi-disciplinary approach in innovation policies for carbon management.

Some of the case studies address the industries that are considered to be the hardest to abate, in particular chemicals, cement, steel and aviation.

Renewable energy is frequently used as the energy source, and several of the countries that submitted case studies are planning for hydrogen to fuel these technologies. Thereby, the net-zero carbon future will go hand in hand with hydrogen, resulting in the need for high levels of investment in both manufacturing and energy technologies.

Biomass features in thirteen case studies, either directly or indirectly. Meanwhile, alternative feedstocks like waste gases and chemically recycled plastics are being developed to complement biomass as sources of renewable carbon.

1

Carbon management: Transcending the bioeconomy

This chapter describes how carbon management strategies transcend the bioeconomy by including recycling of carbon and the renewable energy needed to drive carbon conversion and upgrading. Hence, carbon management should be seen as the integration of the bioeconomy, carbon recycling and renewable energy.

The overall challenge goes way beyond the energy sector

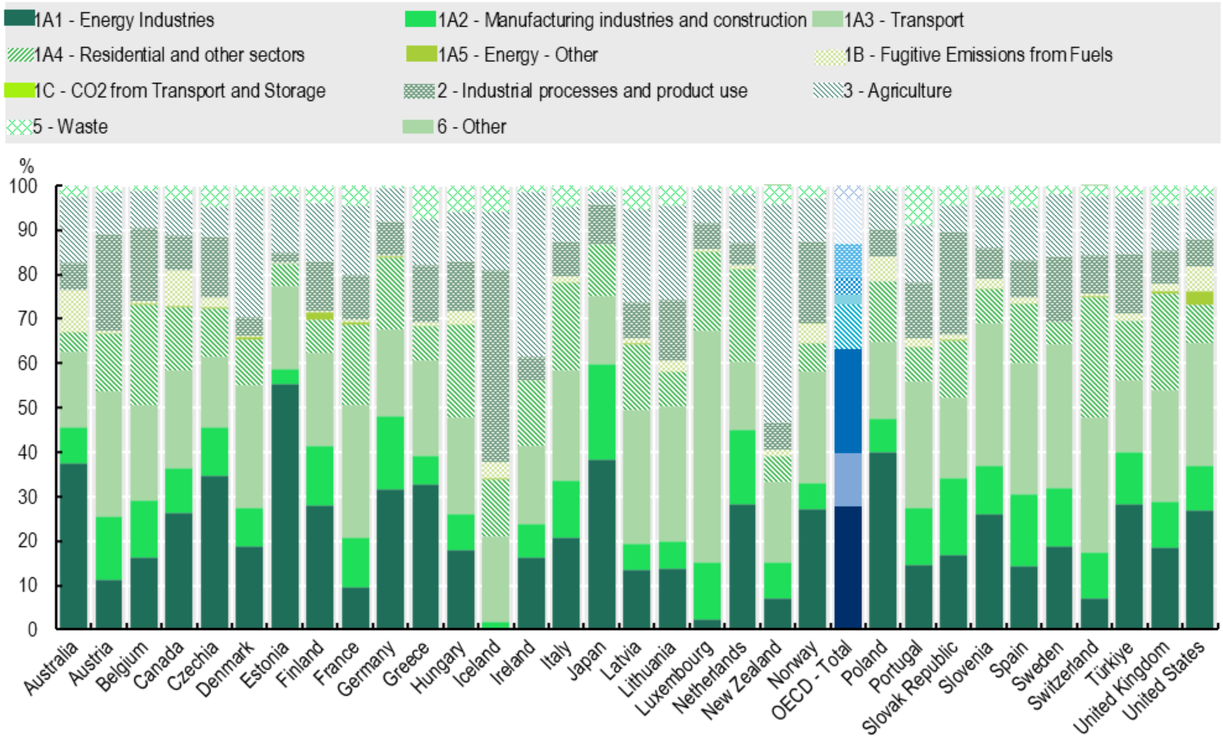
> *"The energy transition is our lifeline. It will enable innovative business models and forms of organisation, transform value chains, redistribute economic power and shape governance in new, more people-centred ways. With the right investments in technology, renewables are the only energy sources offering every country in the world a chance for greater energy autonomy and security".*
>
> *Teresa Ribera Rodríguez, Minister for the Ecological Transition and the Demographic Challenge, Spain*

OECD countries still rely on fossil fuels for about 80% of their energy supply, and while the quote above is certainly true, it gives an incomplete picture of the complexity of the green transition. A strong message is this report is that the transition has to go way beyond energy, where most of the policy is currently focussed. All sectors in all countries need to be involved, particularly those which by necessity involve carbon.

Figure 1.1 highlights the need for action on all sectors. However, for some sectors it will be harder to reduce carbon intensity than for others. Sectors frequently described as the hardest to abate are chemistry, steel and cement (e.g., Paltsev et al., 2021), with the highest emissions of all economic sectors (Broeren et al., 2014). Organic chemicals, which per definition are based on carbon, can obviously not be decarbonised. The chemicals/materials sector is the largest industrial energy consumer and the third largest industrial emitter of CO_2 (Levi and Cullen, 2018) accounting for about 5% of global CO_2 emissions (Gabrielli et al., 2023), and importantly consumes around 10% of global natural gas supply and 12% of all oil (Saygin and Gielen, 2021) as carbon feedstock embedded in the final products.

Figure 1.1. Greenhouse gas emissions by source

%, 2021, territory principle



Source: OECD (2023), "Climate change", in Environment at a Glance Indicators, OECD Publishing, Paris, https://doi.org/10.1787/5584ad47-en (accessed on 07 November 2023).based on OECD, "Air and climate: Greenhouse gas emissions by source", OECD Environment Statistics (database), https://doi.org/10.1787/data-00594-en.

The political and policy urgency

At COP21 in 2015 196 parties agreed to limiting global warming to the ‘2 degree level’ compared to pre-industrial levels. During the COVID-19 pandemic, emissions temporarily decreased, but this was followed by a rebound in the second half of 2020 (Tollefson, 2021) to reach the highest level of all time in 2021[1], despite a surge in commitments to reach net-zero carbon during COP26[2]. The IPCC has warned that unless deep GHG emissions cuts occur within the following decades, it will not be possible to limit global warming to well below 2°C or 1.5°C (IPCC, 2021).

Hence, the primary imperative for governments around the world is the need for urgency in policy making. The previous, post-industrial revolution transitions took many decades to implement (Bennett and Pearson, 2009), but they were unencumbered by the threat of climate change. It is possible that the near-term will be the decisive period that determines success or failure for this transition.

There have been many calls for a green recovery from COVID-19 (e.g., Bell et al., 2021), but governments will only achieve their targets if they take systematic, coordinated policy action to close the gap between long-term commitments and near-term actions, both domestically and internationally[3]. Critical to the near-term actions is a drive to systemic change that will contribute to the 55% decarbonisation required by 2030 (GFANZ, 2021).

Decarbonisation may be misleading

Many countries are planning for net-zero carbon by 2050 and expressing these ambitions as a *decarbonisation* of the economy. While ‘zero carbon’, and ‘decarbonisation’ are justified terms in the energy sector as wind and solar are literally zero-carbon technologies, decarbonisation can be a misleading term in other sectors. In many key industries there is no alternative to carbon e.g., food and feed, organic chemicals, fibres, plastics, and cement.

In such sectors the more relevant term would be ‘defossilisation’ (vom Berg et.al., 2022) that implies leaving fossil reserves in the ground and exploiting other sources of carbon. This is the ‘renewable carbon’ concept which “entails all carbon sources that avoid or substitute the use of any additional fossil carbon from the geosphere” (Carus et al., 2020). Renewable carbon circulates between biosphere, atmosphere or technosphere, creating a carbon circular economy. The decline in oil and gas demand in the net-zero emissions scenarios are hopefully sufficiently steep that no new field developments are required.

The term ‘carbon management’ has historically been used and has become controversial in the energy sector, with mixed opinions and motivations (Okereke, 2007). One interpretation of industrial carbon management is the separation and sequestration of fossil carbon from coal or natural gas (Keith, 2001), while still utilising the energy for generating electricity. However, it is widely agreed that to achieve carbon neutrality by mid-century requires all economic sectors and all countries to participate (European Commission, 2021; Stern and Valero, 2021), hence it is argued that carbon management should be given a wider scope to cover all carbon-based value chains.

The sources of renewable carbon are limited

Future carbon demand will be significantly reduced by decarbonisation of the energy sector. However, even with a major reconstruction of the energy sector, there is justified concern that there is still not enough biomass available to substitute the remaining fossil carbon system without damaging consequences (Kircher, 2022). As an example, aviation fuel consumption in the EU was 62.8 million tonnes in 2018. Using sunflower oil as an aviation biofuel would require almost 60% of EU arable land[4]. (In the United States, however, it has been estimated that 100% of 2050 aviation fuel demand can be met using approximately 70% of biomass that could additionally be produced while maintaining food and feed production).

Organic polymers (plastics) in Europe have about the same volume (64 million tonnes in 2019). Globally, plastics demand is forecast to continue growing to about 1 billion tonnes by 2050 (McKinsey, 2018b). Therefore, even if 60% recycling (mechanical and chemical) was attainable, this implies a fossil replacement of about 400 million tonnes.

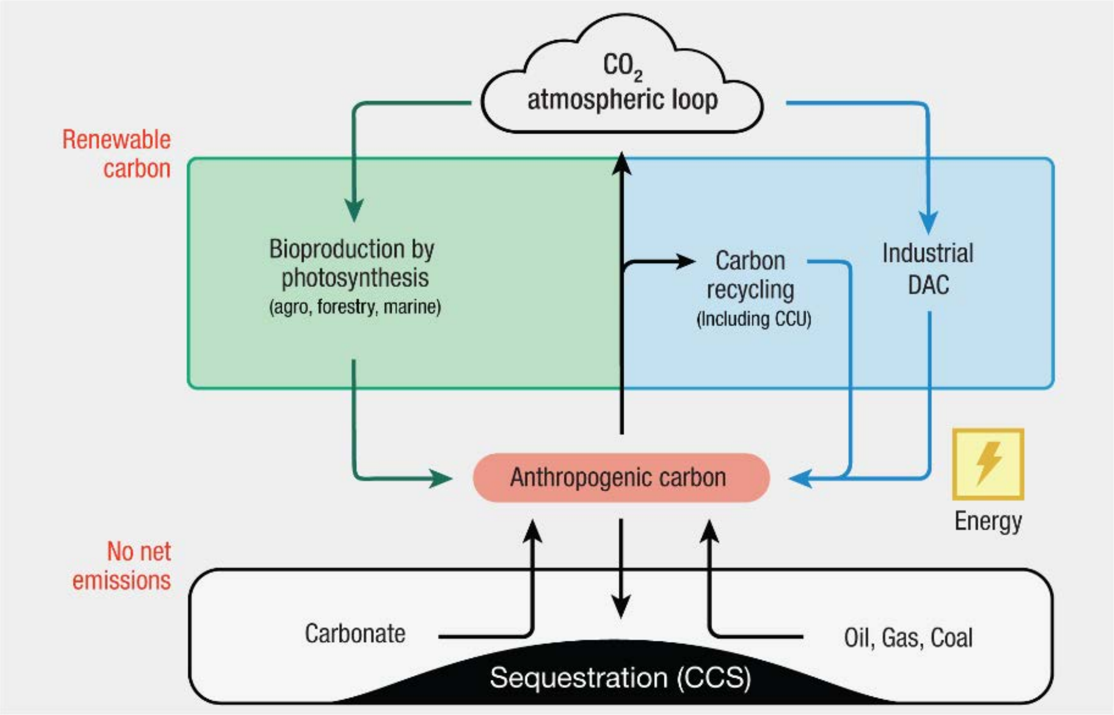
Intensified use of bioresources may lead to increased demand for land, leading to deforestation and biodiversity loss. Planting monoculture crops to support future demand for carbon-based products could have devastating consequences for biodiversity. Prioritising crops for energy, chemicals or materials could in some geographies and contexts negatively affect food prices. In some geographies and contexts, exploitation of agricultural residues is a large potential source of biomass for fuels and chemicals, but such use may also compete with soil management and animal feeds. Efforts to maximise one benefit of land nearly always reduce other benefits (Meyfroidt et al., 2022). Here is enshrined the issue of trade-offs that faces policy makers. The international energy and food price crises of 2022 put these trade-offs in sharp relief.

Given its limited availability, bioresources based on photosynthesis must be complemented by recycling of carbon waste streams, either industry flue gases or solid waste from households or industry. If the technical and economic challenges around industrial fixation of atmospheric CO_2 (DAC) can be resolved (Shayegh et al., 2021), it may become an important future part of the solution.

Any further use of fossil resources must be balanced by permanent sequestration of the emitted carbon, hence creating emission-free resources. This is for instance important in cement production where the use of carbonate minerals is unavoidable or in the use of so-called blue hydrogen in a transition phase. It is important however, to recognise that such compensatory measures may slow implementation of permanent low emission measures.

In this report, carbon management is used to describe policies addressing the complete system of renewable carbon as well as the compensatory activities for hard-to-abate sectors as outlined in Figure 1.2.

Figure 1.2. Carbon management and renewable carbon



Source: (Marvik, 2021).

Recycling as an alternative to bioproduction

An overarching objective of the circular economy is to close material loops to keep carbon circulating in the economy for as long as possible (OECD/G20, 2021). This would break the pattern of 'take-make-dispose' that has characterised the fossil era. By 2019, the first circular economy action plan of the European Union had been completed[5], and a growing number of EU countries, regions, and even cities have been formulating their circular economy strategies and action plans. The circular economy is enshrined in the US National Recycling Strategy[6]. In March 2021, Japan announced their Partnership on Circular Economy in conjunction with the World Economic Forum, and Korea launched the Framework Act on Resource Circulation (FARC) in 2018 (Lee and Cha, 2021).

While the role of carbon capture and utilisation of CO_2 (CCU) in climate change mitigation is debatable, CCU has a clear role in reducing the pressure on bioresources. The many initiatives for carbon capture and geological storage (CCS) create an infrastructure for the supply of concentrated, pure CO_2 as an industry feedstock, pointing to the interplay between CCS and CCU.

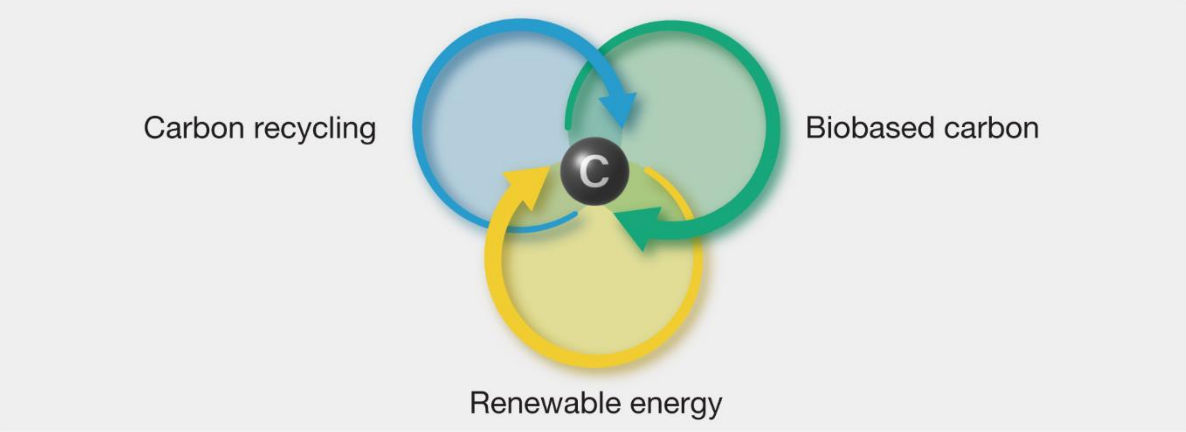
There are potentially many technologies involved in CCU, including biology, chemistry or nanotechnology, and almost all CCU routes use hydrogen as reactant and energy source. Importantly, chemical recycling of solid waste will in many cases involve converting the waste into synthesis gas, comprised of carbon gases and hydrogen, which then may use the same downstream manufacturing processes as for CCU. Eventually, atmospheric CO_2 could also be fed into the same pathway, hence this represents a general industrial platform for renewable carbon.

Global CO_2 production is approximately ten times greater than global oil production today, measured in tonnes. On the current trajectory, this may increase to 20 times by 2050 (IEA, 2012a). While most of these CO_2 emissions are of fossil origin today, this will gradually change as more biogenic and recycled carbon are used in the future carbon economy. VTT of Finland has modelled and evaluated new innovative CCU and CCS concepts for the most important sources of global CO_2 emissions. They concluded that[7] "all transport fuels and most of the chemical products could be produced by using recycled CO_2 and clean hydrogen."

Renewable carbon requires renewable energy

While further research will be required, recycling carbon provides significant opportunities. However, as alluded to above, the carbon cycle is inherently an energy cycle, with energy-poor CO_2 and energy-rich methane (CH_4) as the two extremes. Energy input is therefore needed for most carbon recycling as well as for upgrading of bioresources in many applications. Hence, carbon management should be seen as the integration of the bioeconomy, carbon recycling and the renewable energy required for various carbon pathways (Figure 1.3).

Figure 1.3. Carbon management integrates carbon recycling, the bioeconomy and sustainable energy



Source: (Marvik, 2023).

Energy represents a significant share of manufacturing costs: in the US chemicals industry, for some energy-intensive products, energy accounts for up to 85% of total production costs[8]. Manufacturing with renewable carbon may have at least similar energy needs. This is further illustrated by a study of Kätelhön et al (2019). Here, they show that while CCU has the "technical potential to lead to a carbon-neutral chemical industry and decouple chemical production from fossil resources," this transition would increase the need for low-carbon electricity. They calculated that although CCU in the chemicals industry has the potential for more than 12 gigatonnes CO_2 mitigation potential by 2030, the major caveat it that it would require a clean energy equivalent of 55% of estimated global power production.

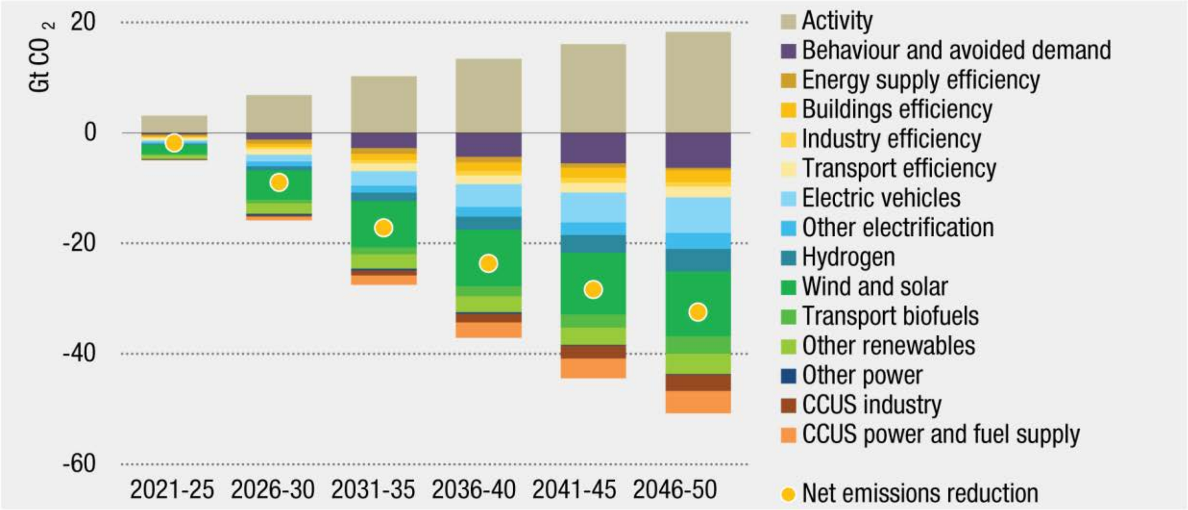
As in many aspects of net-zero carbon scenarios, great uncertainty exists over future energy demand, with most predicting or assuming large increases. Grubler et al. (2018) bucked the trend of ever-rising energy demand, resulting in a lower estimate than comparable scenarios in the mitigation literature. They projected that global final energy demand by 2050 could be around 40% lower than today, despite rises in population, income and activity. They in fact assume that demand for industrial commodities falls by around 15% as a result of dematerialisation and improvements in material efficiency. Obviously, these differences in scenarios pose great challenges for policy makers.

Climate targets depend on CCS and carbon removal

Stabilising atmospheric CO_2 concentrations at 450 ppm, is considered necessary to avoid exceeding 2°C of global warming. To meet this objective, it will be necessary to store 120-160 gigatonnes of CO_2 via carbon capture and storage (CCS) over the next 30 years. There is a need for technology development to both improve resilience to climate change and to reduce GHG emissions, with technology development necessarily complemented by the need for finance in deployment and capacity building.

To reach the emissions reduction targets of the energy sector by 2050, around half of the technologies required by then are not available now (IEA, 2021b). Even so, less than 1% of all recovery spending is directed towards green R&D[3]. The IEA envisages "major roles" for technologies like CCUS in emissions reductions, which will still be growing in capacity by 2050 (Figure 1.4).

Figure 1.4. Average annual CO_2 reductions from 2020 in the IEA net-zero emissions scenario



Source: IEA (2021b)

This view broadly aligns with those of the IPCC (IPCC, 2022). The European Commission considers that "CCUS can play a key role not only in meeting CO_2 emission reduction targets, such as the ones set by the Paris Agreement, but also in accelerating the energy transition and in accomplishing the industry redeployment"[9]. By mid-century CCUS technologies would be capable of mitigating an estimated 14-20% of CO_2 emissions (Ruttinger et al., 2022).

The need for large-scale investments

> *"Only mainstream private finance can match the scale of climate action needed for the net-zero transition including meeting investment needs in emerging markets and developing countries. We cannot get to net zero through niche efforts; we must green the entire financial system, along with every sector of our economies".*
>
> *Mark Carney, former Governor of the Bank of England, co-chair, GFANZ*[10]

The financing of the transition is proving to be challenging (e.g., Pilat, 2022). Given that this green transition is to feedstocks and energy carriers that are often more expensive and less efficient than the fossil resources in current use, then the market will hardly bear the brunt of the cost, at least not in the near-term. **The most immediate policy objective is to stimulate green private investment in large quantities**.

Only four commodities account for almost 45% of industry's CO_2 emissions: cement, steel, ammonia and ethylene. According to McKinsey, the estimated cost of reaching net zero within these four industries by 2050 is USD 21 trillion and does not include the necessary net-zero electricity capacity required to support these industrial transitions (McKinsey, 2018a). This is equivalent to a yearly cost of about 0.4 to 0.8% of global GDP for the next three decades – just for these four industries.

Attracting sufficient capital would require significant coordination and collaboration across governments and industries alike. Public policies must send strong price signals to ensure that renewable carbon and energy efficiency investments offer a sufficiently attractive risk-adjusted return. The Glasgow Financial Alliance for Net Zero (GFANZ), is a private initiative, which collectively represented over USD 130 trillion in assets in 45 countries as of November 2021 (GFANZ, 2021). It is accelerating the best practice tools and methodologies that are essential for "ensuring that the climate is at the heart of every financial decision."

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2 Main policy implications and recommendations

This chapter lays out the main messages and major policy findings derived from an evidence base which consists of: sixteen national case studies from nine OECD member states; four international workshops during the research phase of the project; one workshop post-research; contributions to several IEA/Biofuture Platform workshops leading up to the Clean Energy Ministerial[1]; desk research and detailed inputs from the steering group for this work. As a further aid to policy analysis, the IEA maintains a database of CCUS policies[2].

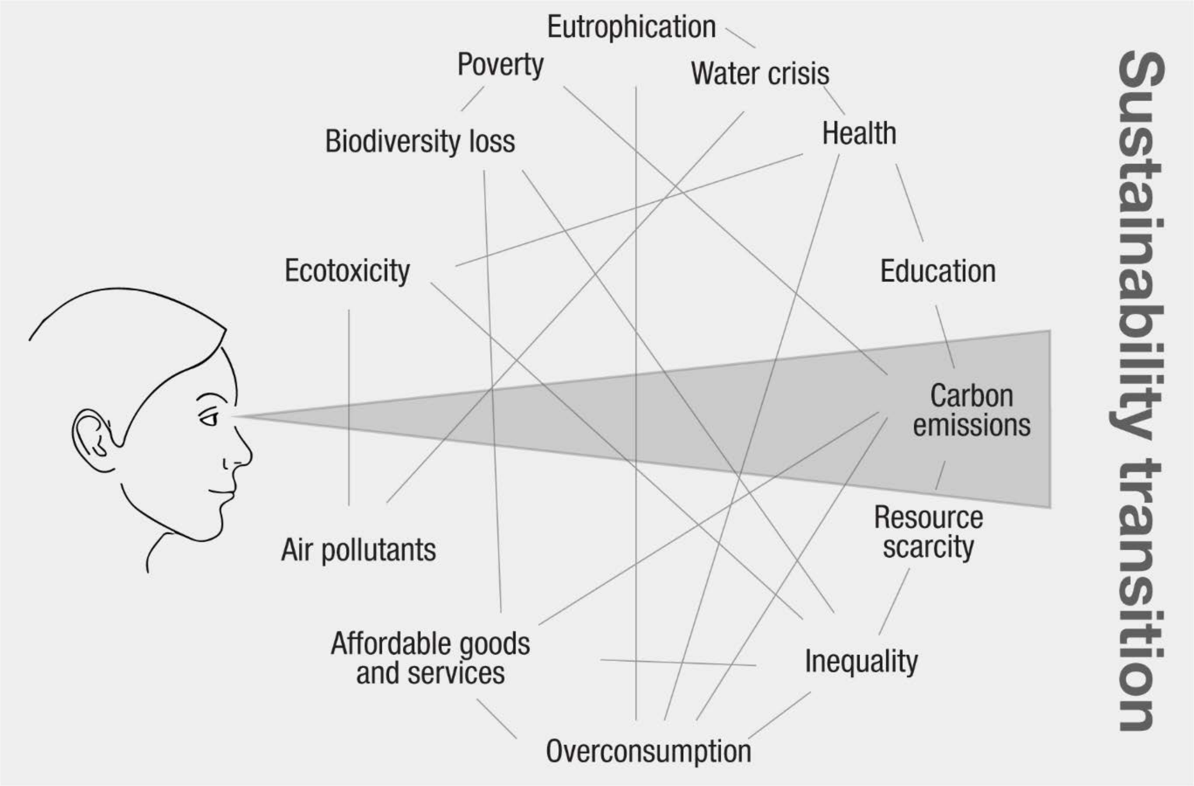
Carbon management – balancing policy trade-offs and dilemmas

Sustainability tunnel vision

With the recent and significant attention given to emission reduction to mitigate climate change, other aspects of sustainability have sometimes been crowded out of policy conversations, creating a potential for unintended consequences that later may need to be reversed (if possible).

What may be called 'sustainability tunnel vision' is to be avoided by policy makers as it may provide a tendency to approve technologies and actions that reduce emissions while simultaneously compromising other sustainability goals, such as biodiversity, water quality, food security (Figure 2.1) For example, evolution takes millions of years to create the current genetic diversity in nature, thus loss in biodiversity is just as irreversible as climate change.

Figure 2.1. Sustainability tunnel vision



Source: Cognizant Research. Graphic by Jan Koniezko , https://digitally.cognizant.com/moving-beyond-carbon-tunnel-vision-with-a-sustainability-data-strategy-codex7121.

National studies increasingly find that the availability of biomass for net zero in industry could be a bottleneck (Fuss, 2021). Many OECD member states are biomass importers. In Norway the import of large volumes of soy protein is essential for its fish farming industry (Norwegian case 1). On the other hand, the United States has done extensive work over a number of years to show the feasibility of being able to resource at least a billion tons of biomass per year sustainably (USDOE, 2017, 2016, 2011, 2005).

Creating a high demand for biomass from countries rich in biomass carries the risk of initiating unsustainable harvesting practices to meet export demand. For example, there are many negative economic, environmental and social consequences of illegal logging (Reboredo, 2013). It already costs nations tens of billions of dollars annually (Lynch et al., 2013), and deforestation and forest degradation account for close to 20% of global emissions[3]. It readily descends into violent crime, warlordism, even assassinations (Nuwer, 2016; Scheidel et al., 2020). Between 15 and 30% of wood traded globally is obtained illegally, rising to 50-90% in key tropical countries (Nellemann, 2012), making deforestation very difficult to control, and creating more than one unintended consequence that would need to be corrected.

The challenge of value-based policies

Carbon footprint, life cycle analysis (LCA), and other sustainability assessment mechanisms represent technical exercises, while balancing different sustainability criteria is an ethical or value-based political process. Hence, the implementation of global policies faces the challenge of obtaining agreement across geographical, economical, ethnic and religious groups, which cannot be solved by rational arguments alone.

In a green transition, values and therefore values-based policies will be given higher priority as there are important issues such as land rights, workers' rights, indigenous people's knowledge and their protection from biopiracy, child labour, forced labour. This is enshrined in the principles of 'just transitions'[4]. With forestry and agriculture and their residues as increasingly exploited feedstocks, policy need to include forest owners, landowners and farms owners. In the European Union alone, there are 16 million private forest landowners, most of them owning small forests (Hetemäki et al., 2017).

Social impact assessment methods still lack a global consensus (Bouillass et al., 2021). Social LCA (S-LCA), while relatively new, is continuously evolving (Marting Vidaurre et al., 2020). S-LCA integrates traditional life cycle assessment but with the focus on social aspects. Sala et al. (2015) presented methodologies and indicators for S-LCA for supporting product policies in order that social and economic benefits can be improved while reducing environmental impacts.

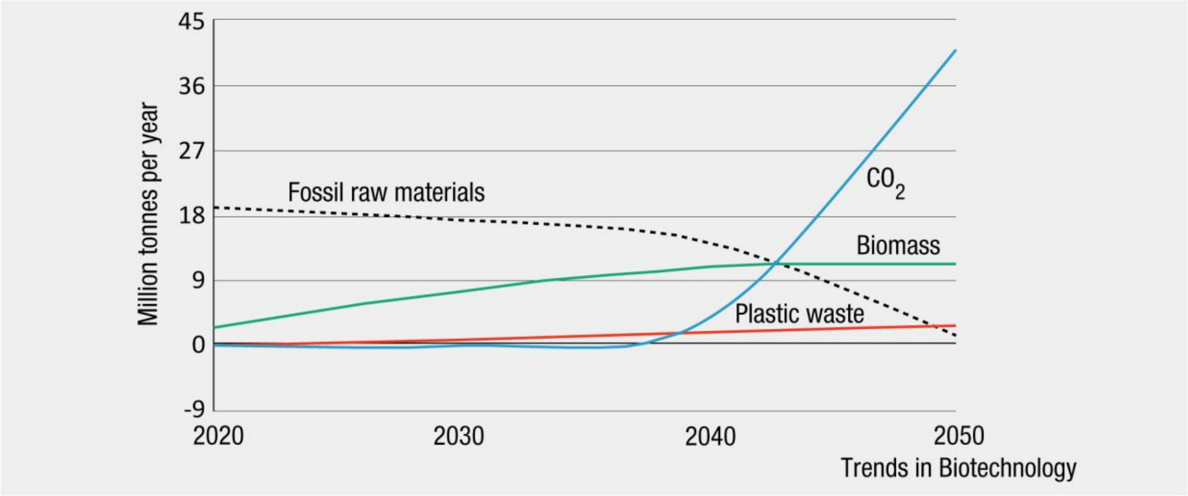
The need to prioritise land use and bioresources

Land use and land use change is a major, if not the major, source of sustainability trade-offs. The concept of indirect land use change (ILUC) (Searchinger et al., 2008) refers to land use change occurring elsewhere when crops used for biofuels and bioproducts displace the production of food or feed. Hence, even when confined to certified feedstock, a general increased in demand may still trigger ILUC. It has proven both controversial and influential, as demonstrated by legislation in countries with low-carbon fuel policies such as Canada, the United States and the European Union to require inclusion of sustainability criteria for biomass feedstocks used in low-carbon fuel production (Khanna et al., 2017). Its measurement has, however, proven inconsistent, reducing confidence in its use.

As sustainable biomass is a limited feedstock, it would be optimal to use the biological complexity and unique properties of biological molecules where it is most valuable and efficient, e.g., food, fibre and bioactives. In other words, optimise for the carbon value instead of the energy value of biomass, an approach broadly consistent with new approaches in the US DOE. It further suggests that it would be a waste to use it simply for energy production or in many cases to decompose it to simple chemical building blocks for the chemical industry. Here, recycling or CCU-derived hydrocarbons would be a better alternative.

This is reflected in Figure 2.2, showing that while biomass will be an important starting point for green chemicals, CO_2 will take over as the predominant feedstock for the German chemical industry from 2040 onwards. A similar prediction is found for sustainable aviation fuel (SAF) in the IEA Net Zero by 2050 scenario.

Figure 2.2. A scenario for future feedstocks of the German chemical industry



Source: Kircher (2020)

A specific initiative within the German plan for the protection of climate, *Klimaschutzplan-2050*, illustrates policies to stimulate the use of CO_2 as a raw material[5]. The Federal Ministry for Education and Research (BMBF) is contributing to the *Klimaschutzplan-2050* under the national framework programme on ‘Research for Sustainability – Fona’[6]. Under Fona, a first funding measure on using CO_2 as raw material was published in 2018: ‘CO2Plus – material use of CO_2 to broaden the basis of raw material’[7].

Further policy aspects of carbon recycling

Conversion of traditional waste streams is seen as the basis for a circular economy and cascading value chains (Klitkou et al., 2019). However, it is important to avoid implementing policies for local recycling of carbon that do not make sense from an overall energy perspective (Hernandez and Cullen, 2019). Indeed, such policies may in fact sub-optimise energy consumption within a larger system. Most industry processes are validated by calculating the mass and energy balances of the process (Larsson, 1992) and carbon conversion technologies need to be subjected to the same scrutiny.

Even if CCU is motivated primarily by a reduced need for bioproduction and stress on land resources, rather than emission reduction *per se*, energy considerations require CCU technologies to be chosen with care. With the right application it may also provide opportunities for mid- to long-term carbon sequestration (Peplow, 2022). While a liquid fuel may return the carbon to the atmosphere very quickly, carbon incorporated in a construction material may have a duration of decades or longer. These aspects of carbon recycling technologies should be preferably assessed in their early developmental trajectories.

Local and international access to key resources

Regional aspects of feedstocks and energy

Biomass and the other renewable carbon feedstocks such as waste recycling, will differ in availability in different regions. Regions and countries need to be aligned in goals even if their strategies differ. Hence, a mostly rural region may have a different strategy from a highly industrialised one. National policy makers will need to be comfortable with different strategies that aim for the same end goal.

Still, regions may find themselves in competition over feedstocks and/or energy carriers. Renewables will presumably alter how regions and countries interact, thereby impacting trade and patterns of cooperation (Scholten et al., 2020) and nations will need to align their foreign and trade policy appropriately.

Government programmes are promoting research and development across supply and value chains, but the markets for supply of material feedstocks and energy receive comparatively less attention (Knight et al., 2015). Uncertainty with respect to key resources is a main factor that deters investors. This lack of attention to supply markets possibly reflects reluctance by governments to be seen to be intervening in markets and potentially contravening anti-competitive practices (Institute of Risk Management and Competition and Markets Authority, 2014).

Analysis points to the potential importance of buyer cooperatives and other forms of supply market intermediaries to facilitate access to bioresources (Knight et al., 2015). This is consistent with the activities of publicly funded regional clusters. Regional clusters are well positioned to evaluate local options, to build capacity in the regions, and then to look beyond the regions (Philp and Winickoff, 2017). Building capacity at the local level depends on business quality and business relationships of trust. Building beyond the clusters can exploit the expertise gained at regional level to expand and join up with other regions. Such clusters can be creating "significant local added value, local jobs and reducing climate emissions" (Refsgaard et al., 2021).

It is important that regions can demonstrate their strengths and weaknesses to national governments in the competition for resources and investment. In the context of smart specialisation[8], France mapped all its regions in detail (Box 2.1). The analysis resulted in a definition of the smart specialisation areas (SSAs) for each region. This policy approach has several advantages and is a model that could be adapted specifically for innovation towards net-zero carbon.

Box 2.1. Defining a smart specialisation strategy for research and innovation in the French regions

> *"In response to the European Commission's ambitions, the French regions have committed to mobilising nearly 20% of the ERDF [European Regional Development Fund] total amount for the first thematic objective concerning research, transfer development and innovation, because innovation and territories are closely linked. While innovation is rooted in the wealth and diversity of territories and their residents, the ability to innovate is a major issue for each territory and a key development and job creation factor".*
>
> *Marie-Caroline Bonnet-Galzy, Commissioner General for Territorial Equality, in: General Commission for Territorial Equality (2015)*

A policy document was prepared as a tool for innovative ecosystem stakeholders and public decision makers to facilitate comparison and cooperation between French regions, including overseas territories. It also helps the regions of other countries to identify the French regions' strengths and envisage collaboration. The tool analysed each region with respect to strengths and weaknesses and mapped key figures like gross domestic (GERD) and business enterprise expenditure (GBERD), as well as numbers of researchers, patents and business creation.

The United States *Billion Ton* reports may give leads on how to harmonise the approaches to biomass sustainability, which vary in underlying methodologies, assumptions and analyses. It is important to effectively estimate the sustainable capacities for biomass production for both domestic use and international biomass trade.

Connecting national to regional approaches was an important element of the Japanese Biomass Towns concept that came out of the 2002 Biomass Nippon Strategy. The strategy sets three types of goals - technical, regional and national, with specific action plans for production, collection and transportation, conversion technologies and for energy or material use (Kuzuhara, 2005). With the encouragement of central government, a total of 318 municipalities participated in making Biomass Town plans (Box 2.2).

While the local dimension of bioresources from agriculture or forestry is obvious, access to other feedstocks like industry carbon gases from cement and steel plants (CCU) or solid waste recycling could also have a local dimension. A typical consideration for a CO_2 emission point is the choice between CCU and CCS. As previously discussed, utilising CO_2 will depend on the local availability of energy, while CCS would typically need either to have road or rail transport of the gases or a dedicated pipeline, to the point of long-term geological storage.

Box 2.2. The Biomass Town Plan policy, Japan

The Biomass Town is an area where a comprehensive biomass utilisation system is established and operated. Each step from biomass generation, conversion, distribution and use is coordinated through the various stakeholders, and, importantly, the activities are appropriate to the local community.

A Biomass Town Plan is a planning document that describes the target area characteristics, implementing bodies, goals and effects, the procedure for developing the plan, biomass potential, and biomass utilisation, all of which eventually contribute to building consensus among various stakeholders to formulate the Biomass Town. Local governments led the development and implementation of the plans to realise Biomass Towns. As such the procedure bears similarities to Smart Specialisation, with a sharp focus on biomass.

Biomass Industrial City

Subsequently, the Biomass Commercialization Strategy was formulated by seven ministries in 2012 and the Biomass Industrial City/Region Scheme, which concentrates on economic sustainability, started in 2013. So far, more than 70 municipalities are recognised as Biomass Industrial Cities/Regions.

Note: See the case study on Saga City Japan (Japan 2: Efforts of CCU by the Saga City cleaning plant). Saga City was certified as a Biomass Industrial City in 2016, with the aim to become a city that recycles waste while creating value as energy and resources.

International feedstock trading

Large quantities of biomass are being shipped around the globe, with most of it destined for OECD countries. However, trading of biomass is controversial, due to many dilemmas. It is reasonable to assume that access to biomass will become a primary strategic asset. As with petroleum, biomass is a critical resource which is not equally distributed, and biomass is thus likely be a cause of international rivalry and disputes (Marvik and Philp, 2020). Today, the strategic importance of arable land is typically related to food security, but access to biomass will also be essential for energy and other sectors, like chemicals and materials.

The energy required to transport large volumes of biomass argues in favour of local utilisation, but in the absence of sufficient quantities of sustainable biomass, import from abroad may be essential. The European Union for example, imports 16% of its biomass needs (Lühmann, 2021). While demand is expected to increase in the efforts to defossilise industry, there is little potential for expanding local production, implying that import is likely to increase. In the UK, the Drax powerplant is an illustrative case. In their efforts to move away from coal, they currently import 8 million tonnes of wood pellets, primarily from North America[9].

Geopolitical shifts may occur, increasing the pressure to harmonise transnational biomass policies. International biomass disputes have already started and there is a need to control this through policy to ensure smooth future trade. An extreme example is the blockage of wheat ready for export from Ukraine during the summer of 2022. Bosch et al. (2015) highlighted biomass disputes that can range from trivial to very serious. For example, the increase in palm oil production in Indonesia from 2006-2010 was accompanied by a range of economic, environmental and social negative consequences (Obidzinski et al., 2012).

In 2015, four of Asia's largest companies were excluded from the Norwegian sovereign wealth fund, the largest in the world, due to concerns over severe environmental damage caused by land clearing at Indonesian palm oil plantations[10]. This was the first time that Norway's central bank made the final decision rather than the Ministry of Finance in an effort to depoliticise the fund. In all four cases, Norges Bank's executive board decided there were no other options but divestment.

Accepting that international biomass disputes are inevitable, there may be a need for the establishment of an international biomass dispute settlement facility (Taanman and Enthoven, 2012) (Box 2.3). In 2013, the Roundtable on Sustainable Palm Oil established a dispute settlement facility[11] (DSF) with these exact matters in mind.

Box 2.3. An international biomass dispute settlement facility (BDSF) as a governance tool

Biomass may be the most controversial of the renewable feedstocks due to its connection to land and land use. A strong ethical component of governance is necessary due to the plethora of environmental and social consequences of non-sustainable overuse of biomass: soil erosion, loss of carbon sink function, biodiversity loss, water pollution, and more difficult to quantify, social issues such as indigenous people's rights, workers' rights, child labour, fraud, illegal logging.

The idea for a BDSF was explored by Taanman and Enthoven in 2012 for the Netherlands Department of Economic Affairs, Agriculture and Innovation and the City of The Hague. Thirty-five stakeholder interviews were conducted and unanimously all interviewees expected that the number of biomass conflicts will increase in future as pressure on available fertile land grows.

Joint fact finding, negotiation, mediation, arbitration and judicial settlement are the main mechanisms for dispute settlement. International organisations prioritise mediation and arbitration over judicial settlement (Allee and Elsig, 2015).

Accounting for carbon in imports and exports

Disputes and carbon management intersect when carbon-containing goods and biomass are exported around the world. The import of carbon-intensive goods from a country with less stringent climate action controls is open to unintentional or deliberate abuse by the importer and the exporter. Exporting countries can shift production to countries with lower controls. Importing countries can have products replaced by more carbon-intensive imports.

The EU Carbon Border Adjustment Mechanism (CBAM)[12] is considered a "landmark tool to put a fair price on the carbon emitted during the production of carbon intensive goods that are entering the EU, and to encourage cleaner industrial production in non-EU countries". The CBAM is meant to ensure the carbon price of imports is equivalent to the carbon price of domestic production, and that the EU's climate objectives are not undermined. Moreover, the CBAM is designed to be compatible with WTO-rules.

Training the workforce of the future

The need for a specially trained workforce will exist throughout the different technologies of the green transition. While competence in chemistry or engineering will remain key in green manufacturing, some emerging technologies would be crucially dependent on unique skills.

In the burgeoning synthetic biology industry for instance, the skills and education of the workforce is considered by many to be a key pinch point for the industrial development. However, it is argued that at least 30 PhDs in biology and biochemistry are available for every technical engineer (Kitney et al., 2021), thus what could be missing is the training of engineers, mathematicians and computer scientists with a basic understanding of biology.

While much attention is directed towards training of PhDs, a workforce development programme needs to be much broader, for instance by including apprenticeships and day-release education. Higher education is rising to the challenges with a diverse range of solutions from technician training, massive open online courses (MOOCs) and business management courses (Philp, 2022).

Interdisciplinarity implies a problem-solving function not necessarily implicit to multidisciplinarity. A useful distinction was made by Boix Mansilla et al. (2000) who framed interdisciplinarity as the capacity to integrate knowledge and modes of thinking in two or more disciplines.

This, in fact, challenges the teachers as much as the students: MacLeod (2018) stated that “traditional scientific education and training has remained divided by disciplines such as microbiology, chemistry and computing. The challenges to higher education remain on many levels”. Multi- and interdisciplinary education would break this silo situation to create graduates more adept at problem solving.

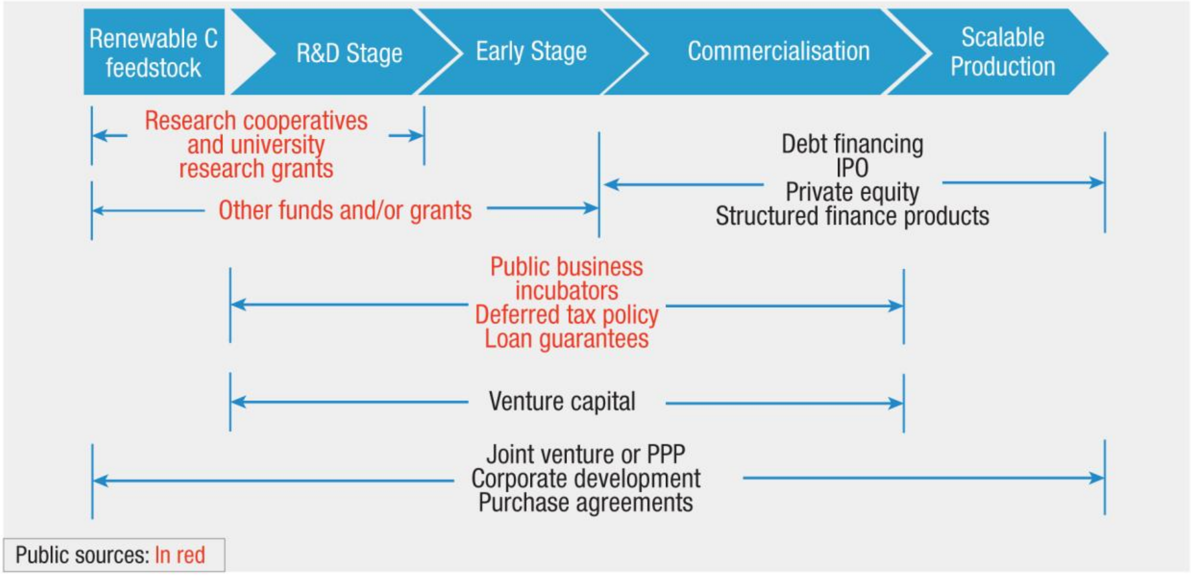
Public R&D support for carbon management technologies

Selection criteria for innovation support programmes

In business literature, innovations have been considered the most critical driver of economic growth (e.g., Shakina and Barajas, 2020). In principle, public subsidies should support innovation programmes with the largest value for society (Nicolaides, 2013), but R&D alone is not always the most efficient tool to reach climate targets, which may require more specific selection criteria and coupling to market stimulation (Fischer and Newell, 2007).

Innovation policies range from framework conditions, generic measures to support the business population to more targeted direct (grant or loan funding) and indirect (e.g., R&D tax credits) measures for SMEs and entrepreneurs. As such, often a wide number of ministries and agencies across government at both central and subnational level are involved. This makes for a complex domain to deliver effective, efficient and coherent policies. Figure 2.3 is an adaptation of a diagramme from the Milken Institute (2013) showing the major steps along the way.

Figure 2.3. Funding renewable carbon technology development



Source: Adapted from Milken Institute (2013)

The vast array of technical challenges in carbon management indicates the need for hybrid technologies if any one technology does not meet all requirements of economic and environmental benefits. For example, a biotechnology process used to generate small-molecule intermediates followed by chemo-catalytic conversion to larger fuel molecules is likely to reach commercialisation faster than biotechnology alone (Lynd et al., 2022). This may create difficulties for government agencies responsible for grants and investments in these technologies due to the multi-disciplinarity inherent in building hybrid processes.

For innovation in carbon management, it is especially important to combine both techno-economic and environmental assessment that can reveal the impact of policy incentives (Scown et al., 2021). No environmental impact model exists that accommodates all aspects of circularity (Das et al., 2022). When recycled and renewable materials are involved, mass balance analysis is a chain-of-custody approach to account for materials entering and leaving a system.

The mass balance approach is typically used in the chemical industry, where the volume of renewables is allocated to take account of all yields and losses[13]. Mass balance of materials may be obvious, but just as important is energy consumption. Funding a project that makes sense in terms of materials, but does not make sense from an energy perspective, may result in public money being wasted.

Development of carbon management technologies may be particularly difficult for startups and SMEs, as the timeline and cost of realising a new technology or process can be prohibitive. Moreover, these emerging processes will typically support a public good, rather than a well-defined consumer need, thus public funding bodies should be prepared to accept immature markets and higher market risk than has been the norm.

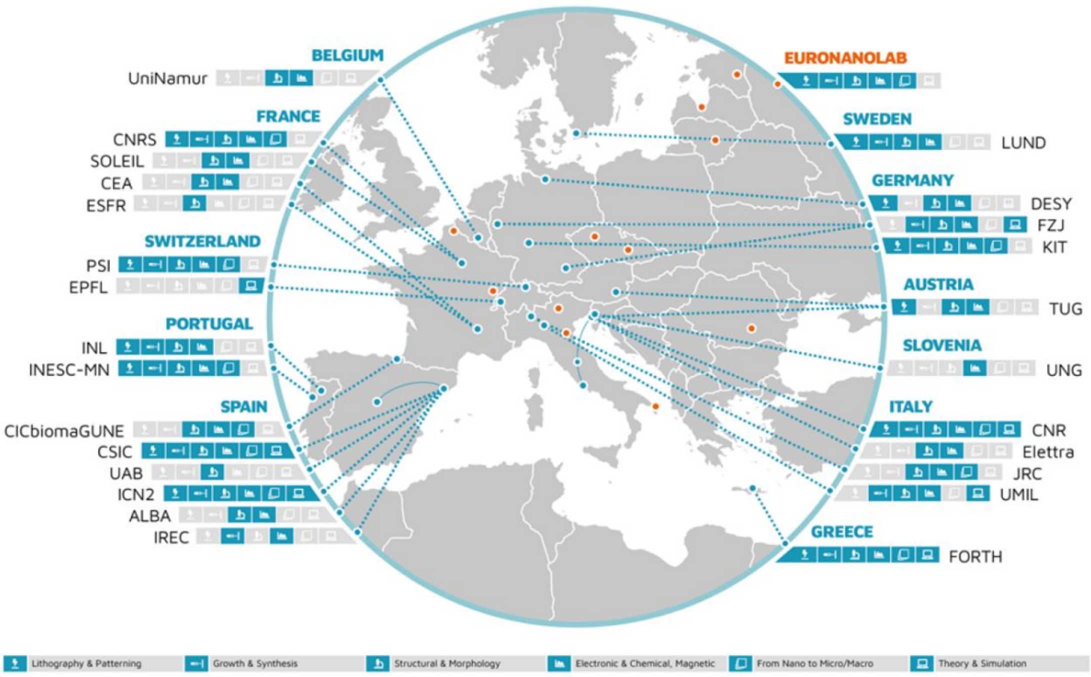
In order to increase the chances of success, R&D programmes are often reinforced by auxiliary programmes. SynbiCITE[14] is the industrial translation engine for seven key UK synthetic biology research hubs. SynbiCITE supports the growth of companies (start-ups and SMEs) in synthetic biology by providing scientific and technical support through its staff scientists working in the context of an advanced biofoundry. In addition, SynbiCITE provides business support and business courses (Basic Business and Lean Launchpad). In 2022 a new investment company was created (SynBioVen) with an investment of GBP 20 million to partner with SynbiCITE.

Greater efficiency of public investments might be obtained through the public finance of production facilities at pilot and/or demonstrator scale, although the benefit needs to be proven. Models already exist e.g., the GBP 24 million Centre for Process Innovation (CPI)[15] in the UK. CPI helps SMEs understand the commercial feasibility of products or processes in a way that reduces risk to the companies and their investors. Such facilities could maximise their benefits by offering a range of ancillary business services, such as training, quality management and certification (Schieb and Philp, 2014).

Support for an emerging technology seen as a public good justifies a strong focus on targeted instruments for R&D, but also realising that broadly based R&D programmes complement targeted instruments as they can discover new applications from more blue-sky research and answer fundamental research questions of low value to the private sector. In other words, science and science funding should adapt to combine curiosity driven science with science more relevant to society's needs (Rodrigues, 2021).

A relevant example is the open access NFFA consortium for nanotechnologies[16]. NFFA is a pan-European consortium of 22 international partners with a core of 13 co-located foundries and large-scale facilities (Figure 2.4). It allows researchers to face complex nanoscience challenges that cannot be provided by any single research infrastructure alone. Supported by the Horizon 2020 Pilot project, it offers free of charge access for academia and industry.

Figure 2.4. The NFFA consortium



Source: NFFA-Europe, www.nffa.eu/about.

Prize competitions as an innovation driver

Fixed contracts, grants and prizes all have roles in the innovation process, and prizes have been hailed for some advantages. One purported advantage is that they can build a larger community of practice compared to, say, grants, as inducement prize competitions tend to be open to an audience wider than technical experts. Experience at NASA suggests that prizes work best when the government can articulate a specific problem requiring solutions which can leverage private sector market demand (National Academies of Science, Engineering and Medicine, 2020).

The XPRIZE for Carbon Removal[17] is the largest inducement prize in history at USD 100 million. It is a four-year competition open to teams from anywhere on the planet, with the objective of specifically pulling CO_2 from the oceans or atmosphere and to sequester it sustainably. To win the grand prize, teams must demonstrate a potential for scaling:

- Demonstrate a working solution to remove at least 1 000 tonnes per year.
- Model their costs at a scale of 1 million tonnes per year.
- Show a pathway to achieving a scale of gigatonnes per year in future.

Industry clusters set to enhance innovation

The main rationale for public policies to promote technology clusters through infrastructure and knowledge-based investments, networking activities and training is an increase in knowledge spillovers among actors in clusters (Box 2.4). This is purported to generate a collective pool of knowledge that results in higher productivity, more innovation and an increase in the competitiveness of firms.

Technology and regional clusters are a leading support mechanism for SMEs (Wilde and Hermans, 2021), providing a range of services, such as: access to venture capital and other finance routes; business advice on the strategic use of standards, labels, certificates, assistance with specific LCA and sustainability tools, access to demonstration and testing facilities. National government programmes can provide a wide range of support mechanisms for clusters, especially exemptions from tax and national insurance payments.

Box 2.4. Cleantech Cluster, Lithuania

There are many relevant clusters to choose from in Europe as the publicly funded cluster model has proven very popular. The motivations and competencies of Cleantech Cluster Lithuania illustrate the typical capabilities of clusters. Cleantech Cluster Lithuania connects clean technology companies, science and research institutions and other entities that contribute with their professional knowledge, skills, business activities, reputation and experience.

Collaboration: Members collaborate in developing new solutions, products and services, participate in public tenders and international funding programmes.

Corporate image: Membership in the cluster creates added value for the company offering features of responsibility and sustainability.

Networking: Cluster membership allows access to specialised information and contacts with decision makers. The cluster coordinator engages in lobbying and networking.

Innovation and finance: The cluster promotes innovation, creates a better environment for R&D, reinforces the value chain of the clean technology sector and facilitates access to investment.

Source: https://cleantechlithuania.lt/en/#apie

Other financing instruments for green projects

As shown in Figure 2.3, several funding mechanisms and financial instruments may be relevant as projects progresses. Green Bonds is a further option to enable capital raising for new and existing projects with environmental benefits. The Green Bond Principles[18] instrument is a mechanism to mobilise large capital sums, with the financing and management of project risks undertaken by the project sponsors, not the investors that might or might not have the capacity to manage said risks.

Green Banking can serve climate goals by financing climate change mitigation technologies hand-in-hand with the private sector. A government-backed green investment bank differs from a typical fund in that it should not just disburse government money, but as a bank it should be able to raise its own finance and fill a gap in the market for government-backed bonds, bring in banking expertise and offer a range of commercially driven interventions - loans, equity and risk-reduction finance. As a publicly capitalised entity, a green investment bank may facilitate private investment into domestic low-carbon and climate-resilient infrastructure and other green sectors such as water and waste management. These dedicated green investment entities have been established at national level and at state and even city level (OECD, 2016). Akomea-Frimpong et al. (2021) reviewed various instruments for green banking.

The UK government has created an Infrastructure Bank[19], capitalised with GBP 22 billion to fund low-carbon investment and rapidly scale up operations. It is meant to be a key instrument for the United Kingdom to meet its net-zero emissions target by 2050. This is partly a response to the UK Energy Security Bill outlined in April 2022. It also coincides with appointing Ofgem[20] as the new energy regulator to ensure consumers get heating at a fair price.

The root problem: Sustainable alternatives are often less competitive

Public market stimulation is necessary

This green transition to net-zero carbon by 2050 is fundamentally different from the major transitions since the first industrial revolution. The transitions from wood to coal and coal to oil were transitions to more efficient feedstocks and energy carriers, but with the key component of pollution as an unpriced market externality. As a result, the market was dominant in their uptake, never having to bear the economic cost of pollution.

In this green transition, however, the opposite pertains, and in the absence of public policy this makes the transition unattractive to the market. Thus, in the green transition many markets based on renewable carbon will need to be driven by policy. New carbon supply chains depend on novel technologies; hence implementation of carbon management is strongly connected to innovation policies.

Table 2.1 shows a simple example of how carbon tax could influence the relative attractiveness of CCS, CCU and DAC. If the carbon tax is too high, CCS would probably be preferred. This would benefit climate, but not biodiversity. If, on the other hand, market incentives are strong, carbon recycling (CCU) would be more attractive, potentially reducing the pressure on bioresources. While DAC technologies are at an early stage of development, DAC may eventually become a significant alternative to biomass (Fuss, 2021). Policies will determine the relative attractiveness of CCS, CCU and DAC, as illustrated in Table 2.1. Thus, assuming a combination of high carbon tax and strong market stimulation, DAC may become a preferred option, both from a commercial and a sustainability perspective.

Table 2.1. Policies will determine the attractiveness of CCU

Policies for:	Supply side	Demand side	Sustainability benefits
Continued emissions	Low	Low	Business as usual
CCS	High	Low	Stimulating decarbonisation but no benefit for land use and biodiversity
CCU	High	High	Reducing pressure on bioresources but limited climate mitigation effects
DAC	Extra high	Extra high	DAC becomes competitive to CCU: Benefits for climate as well as bioproduction and biodiversity

Source: OECD (2022)

Public policies will have to make choices

As many markets in the green transition depend on regulations, it is unavoidable that public policies take a role in selecting the trajectories towards a more sustainable society. It further implies that public policies will be involved in prioritising technologies and technical pathways in the new green supply chains. This report aims to guide policy makers in their implicit choices of technology platforms and associated feedstocks as they negotiate the uncharted waters of innovation and potential unintended consequences.

Urgency creates a dilemma for governments. From upstream research through downstream R&D&I to demonstration/flagship projects, urgency dictates that failures have to be minimised due to the proximity of 2050. This calls for careful selection of projects for public funding and intensive scrutiny of value chain and public-private partnership stakeholders. Selection criteria have to go beyond good science and engineering to include techno-economic assessments, resource availability, social impact assessment, and environmental credentials (not necessarily just emissions reduction).

The term ‘picking winners’ first arose in the context of technology foresight in 1983, the message being that this is exactly what government *should* do i.e., invest in emerging technologies that could enable economic development (Irvine and Martin, 1984). This was in direct conflict with the ideology that the market should do the picking, not governments, with the argument that governments are ill-equipped to do so. The one-off logic of picking winners has been largely rejected.

On the other hand, it can be argued that a core function of government is to supply public goods or benefits (e.g., climate change mitigation) that markets either fail to provide or cannot provide efficiently (Anomaly, 2013). Given the short-term run up to 2050, it is critical that the optimal outcome technology paths are chosen. Hence, the ‘picking’ should be based on societal benefit criteria and assessment procedures involving both public and industry considerations. In conjunction with industry, philosophy could change to “creating winners” (White and Wilkinson, 2017) and retaining them (Autio and Rannikko, 2016) rather than picking them. For retention, Autio and Ranniko argue for policy initiatives that:

1. are highly selective, e.g., requesting evidence for emission reductions
2. emphasise strong growth motivation as a key selection criterion
3. control milestone achievements and condition support on achievement
4. promote the exchange of insights on how to effect rapid organisational growth
5. rely on public–private partnerships for hands-on, capacity-boosting support.

Note that none of these recommendations question the technology-neutrality principle. Actual emissions reduction technology and trajectory selection should be technology-neutral, which has long been a favoured principle in governments for the design of policy in areas characterised by rapid technological change (Aisbett et al., 2021), and is especially relevant to hybrid technologies (see Policies to stimulate industrial symbiosis).

Project assessment framework to guide public investment

A diversity of sustainability criteria and certification schemes

There are many proposed indicators of sustainability[21], far too many for it to be immediately apparent which can be used to measure sustainability. In addition, there is no collectively agreed-upon definition, making measuring sustainability difficult (El-Chichakli et al., 2016). Moreover, as discussed in The challenge of value-based policies, the challenge is exacerbated by the difficulty of value-based comparison of different sustainability objectives.

Today, theories of sustainability rest on three pillars: economic, environmental, and social – some remain more difficult than other to measure. While there are standardised methodologies for measuring economic and environmental aspects, social aspects are much more difficult to quantify (van Dam and Junginger, 2011). Furthermore, sustainability frameworks that focus on social implications also may bear a more holistic meaning of sustainability by including the health and well-being of people and societies (Shawki, 2016).

Tools used to measure environmental impacts include Input/Output Analysis, Life Cycle Assessment (LCA), Material Flow Analysis, Recycling Efficiency Rate, Global Reporting Initiative (GRI), and GHG Indicators. LCA is the most commonly used approach, and its ability to quantify means that it can be used to compare environmental impacts of different processes and manufacturing systems. Social LCA, as discussed, focuses on social impacts of the product and hence can address organisational aspects of the value chain. Life cycle costing (LCC) assesses all the costs of a product during its entire life cycle.

While all of these tools have their pros and cons, there is no one single consolidated tool to date. In fact, there is no internationally agreed framework for measuring biomass sustainability, no agreed criteria and no agreed tools for measurement (Bracco et al., 2018) and none of the tools available is robust enough to cover sustainability in all three pillars (Iacovidou et al., 2017). There is at least one international journal, *Environmental and Sustainability Indicators*[22], dedicated to the subject.

Sustainability indicators should be easy to use and certification systems inexpensive to incentivise uptake by SMEs as they comprise the bulk of private companies. Without commonly agreed upon and standardised tools and frameworks, the unintended consequence could result in *de facto* standardisation of competing sustainability indicators and frameworks, leaving private companies at odds with government climate goals (de Freitas Netto et al., 2020). There is a surprising lack of empirical studies on how companies are measuring the environmental impact of their business in practice (Das et al., 2022), which reinforces the need for policy intervention.

Currently, the UN Food and Agriculture Organization (FAO) is developing a methodology for assessing sustainability of bio-based products. It recommends a step-by-step approach to sustainability assessment that considers all three pillars, and also differentiates between territorial and product assessments. As part of this approach, countries or producers and manufacturers are provided with a long list of scientifically robust indicators, from which to choose a limited set of core indicators that suits their needs and circumstances (FAO, 2019).

There are various private sector suppliers of sustainability certification schemes (SCS), notably the Roundtable on Sustainable Biomaterials (RSB) and International Sustainability and Carbon Certification system (ISCC). The ISCC system[23] covers all sustainable feedstocks, including agricultural and forestry biomass, waste and residues, non-biorenewables, recycled carbon materials and the respective supply chains. It is also notable in its coverage of sectors; it is already used globally for the chemical industry, packaging, industrial applications as well as in the food, feed and bioenergy markets (Schmitz, 2020).

The importance of standards and certification in policy

Stringent standards and certification give confidence to consumers and industry as they provide credibility to claims of performance and sustainability (Dammer and Carus, 2015), such as ‘bio-based’, ‘renewable raw material’, ‘biodegradable’, ‘recyclable’, or ‘reduced greenhouse gas impact’. They help verify claims such as biodegradability and bio-based content that will promote market uptake (OECD, 2011). Third party verification is a means to prevent unwarranted claims and greenwashing.

According to the British Standards Institution (BSI), a surprisingly large proportion of annual productivity growth can be attributed to standards (BSI, 2015). Companies can use matching or beating a standard as an R&D and marketing tool, which then spurs competitors to innovate further, driving technical advances and delivering efficiencies. Standards are typically developed in close cooperation between industry, research and policy makers, which is essential to create the right environment for new products and technologies to grow to full-scale deployment.

Standards and certification schemes are also joining-up measures between policy frameworks and practical implementation. Standards provide the necessary scientific basis for implementing legislation by demonstrating compliance with legal requirements. Similarly, they are essential for all public market intervention, and they are important to verify that policy goals and targets are being met.

The inadequacy of industrial classification codes

National industrial classification codes have multiple important functions. One of these is to enable market and economic analysis in specific sectors and sub-sectors. Unfortunately, their usefulness to measure the progress of the green transition is often limited.

By way of example, Carlson (2016) found that in the United States it was impossible to (economically) distinguish a bio-based chemical and the identical chemical made from fossil resources. This is because there is no North American Industrial Classification System (NAICS) code (Executive Office of the President of the United States, 2017) for these products. The only relevant code is for a subset of pharmaceutical production. However, for the 2022 revision, the US Office of Management and Budget (OMB) has accepted recommendations with respect to bio-based products manufacturing and renewable chemicals manufacturing, including the decision to "continue research and outreach in this important emerging area" (Federal Register, 2021). A team is in the process of making recommendations in this space and is currently drafting a Request for Information.

Similarly, Ronzon et al. (2020) described the challenges in estimating 'bio-based shares' for sectors which only partially belong to the bioeconomy, as reported in the European NACE (*Nomenclature Statistique des Activités Économiques dans la Communauté Européenne*) classification[24]. NACE codes refer to "fermentation of sugarcane, corn or similar to produce alcohol and esters" (European Commission, 2008), but there is no general classification system for chemicals or materials based on biomass or other renewable carbon sources.

Market intervention to encourage private investments in renewable carbon

The most pressing need for the net-zero carbon transition is investment, both private and public. As demonstrated, the green transition is an overhaul of global economics and environmental commitments, with far-reaching social ramifications. The financial commitments are significant, being measured in the USD trillions by 2050. Initially this focus was on energy and transportation transformation, however it has become clear that it must involve all sectors and all countries.

While only mainstream private finance can match the scale of climate action needed for the net-zero transition, it is unlikely that the ambition will be realised without large concomitant public funding to de-risk private investments. Unfortunately, there is little room for manoeuvre as time is of the essence, and public investments have to be efficient, maximising climate effect while minimising failures. Therefore, not only do public investments need to protect private investment through de-risking, but the public investments also need protection.

Hence, the overarching challenge for government policies in general is to encourage investment in renewable carbon technologies while discouraging further investment in fossil. On the supply side a major push is required to de-risk private investments in testbeds, pilot and demonstration facilities. Large public investments are needed to get emerging technologies to an advanced stage. Equally urgent are policy measures to develop the demand-side (market) to make private investments flow. Market interventions must be consistent over time, however, as market uncertainty is lethal to private finance.

Tax incentives have become a favoured policy tool that governments use to encourage companies to invest in R&D (OECD, 2020b). The sums required for technology deployment are likely to be much higher than in R&D, especially in capital projects and those requiring bespoke or highly specialised large-scale equipment. In the United States, federal production and investment tax credits have helped promote the development and deployment of wind and solar energy technology and more recently CCUS technologies. Similarly, Canada (Box 2.5) has introduced tax incentives from the CCUS sectors, while Denmark has chosen a strategy based on contracts for difference[25].

Box 2.5. Canadian investment tax credit for CCUS

The 2022 Canadian Federal Budget of April 7 establishes a refundable investment tax credit for Carbon Capture, Utilisation and Storage (CCUS) beginning in 2022. The CCUS Tax Credit follows the announcement of its 2030 Emission Reduction Plan for achieving a net-zero economy by 2050.

The tax credit seeks to incentivise CCUS technologies that capture CO_2 emissions (from industrial processes, fuel combustion, or directly from air) for storage or utilisation in industrial processes. It will offset the costs of purchase and installation for eligible equipment.

The CCUS Tax Credit is offered on a sliding scale on the cost of purchasing or installing eligible equipment incurred in a taxation year, provided that the eligible equipment is used in a CCUS project for an eligible use. For the years 2022-30 the CCUS Tax Credit is:

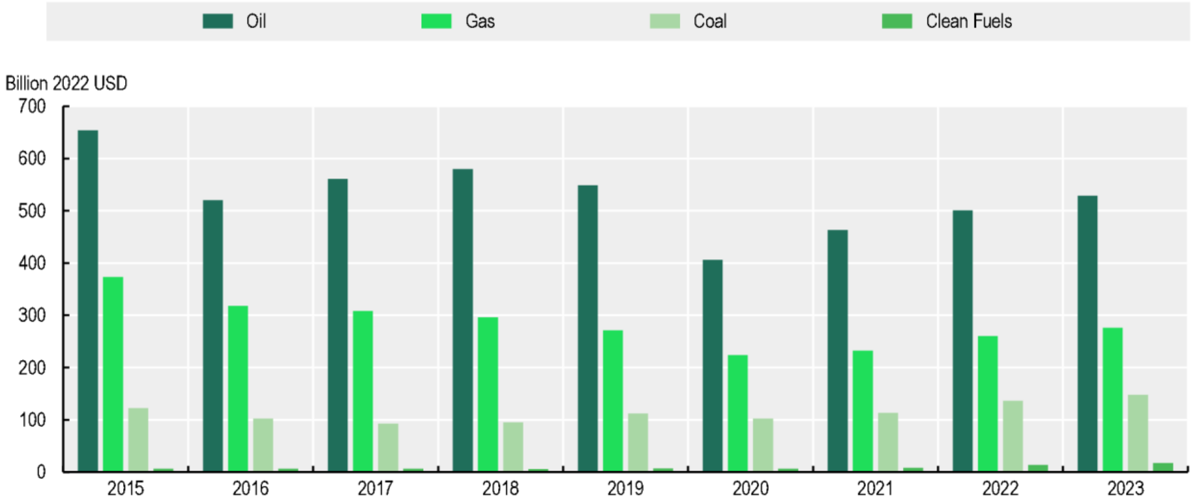
- 60% for eligible capture equipment used in a DAC project
- 50% for other eligible capture equipment
- 37.5% for eligible transportation, storage and use equipment.

Source: Johnson et al. (2022).

‘Stick policies’ – lower dependence on continued use of fossil carbon

The advantages that fossil holds at present are so overwhelming that governments need to create greater balance. In fuels and energy, where the policy is most mature, the gulf to be crossed is still stark (Figure 2.5). The lack of a level playing field is greatly exacerbated by large-scale fossil fuel subsidies, many of which are at odds with an industry over 100 years old. Combining fossil fuel subsidy reform with a realistic carbon price and carbon tax are the two most obvious ways to encourage investment in renewable carbon use and necessary for meeting the United Nations sustainable development goals (SDGs) (El-Chichakli et al., 2016).

Figure 2.5. Global fuels investments demonstrate the reality of the competition between fossil and renewable energy



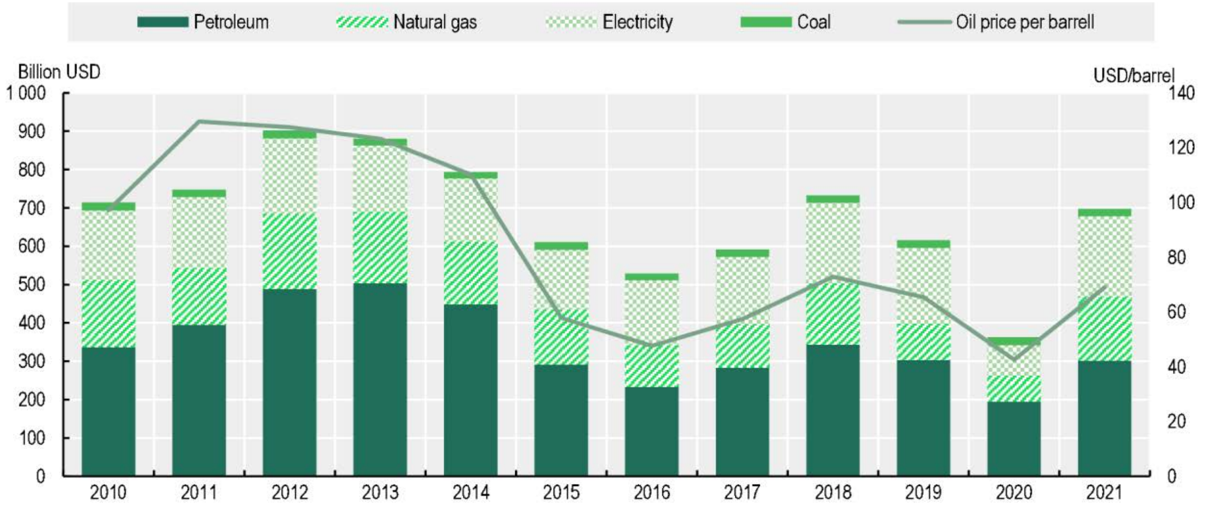
Source: IEA (2023), World Energy Investment 2023, IEA, Paris www.iea.org/reports/world-energy-investment-2023, License: CC BY 4.0

An IEA analysis has suggested that no further new investments in fossil fuels should be made if 2050 climate goals are to be reached. However, planned investments within the oil majors, both private and state-owned, show that the industry is preparing for massive investments[26]. In response to that article, Fatih Birol of the IEA “warned against investing in large new oil and gas developments, which would have little impact on the current energy crisis and soaring fuel prices but spell devastation to the planet”[27].

Discontinue fossil fuel subsidies

Monitoring fossil fuel subsidies, the IEA has routinely returned annual subsidy figures in the region of USD 0.5 trillion. The International Renewable Energy Agency (IRENA) tracked USD 634 billion in total energy-sector subsidies in 2020 and found that while around 70% went to fossil fuels, 6% went to biofuels and just over 3% to nuclear (IRENA, 2020). OECD calculations showed a significant drop in subsidies during COVID-19, with a predicted surge in 2021[28] as economies reopened (Figure 2.6).

Figure 2.6. Fossil fuel subsidies fail to reach those in society that would most benefit



Note: Data for 2021 are on a preliminary basis.
Source: IEA/OECD press release (2022) "Support for fossil fuels almost doubled in 2021, slowing progress toward international climate goals, according to new analysis from OECD and IEA www.oecd.org/environment/support-for-fossil-fuels-almost-doubled-in-2021-slowing-progress-toward-international-climate-goals-according-to-new-analysis-from-oecd-and-iea.htm (29 August 2022)

Fossil fuel subsidies challenge governments' net-zero pledges while swamping investment in sustainable energy infrastructure. Governments could use the money saved by scrapping these subsidies to fund decarbonisation projects and technologies. The International Institute for Sustainable Development (IISD) has estimated that removing fossil fuel consumption subsidies in 32 countries would cut their GHG emissions by an average of 6% by 2025 (IISD, 2021).

While most of these fossil subsidies are inefficient and wasteful, their removal has proven difficult (OECD, 2020a) and is exacerbated by international crises. For any country attempting reform, removing such subsidies all at once could cause serious economic reverberations, with the possibility of social unrest, as was seen in Ecuador in 2019 when a fuel tax hike was introduced (Timperley, 2021). Kazakhstan, in the top 25 countries for fossil fuel subsidies[29], erupted in violence in 2022, sparked by a rise in the price of liquefied petroleum gas (LPG)[30].

What has been working, however, is a self-peer review process. Since 2013, G20 countries have developed and implemented a methodology for voluntary, country-led peer reviews of fossil fuel support as a "valuable means of enhanced transparency and accountability" (OECD/IEA, 2021). While some countries have made progress in reducing or phasing out these subsidies, others increased subsidies as part of rescue and recovery from the pandemic-induced crisis (OECD/IEA, 2021).

Fossil carbon emission taxes

Carbon taxes and emission trading systems (ETS) are the most cost-effective means of reducing CO_2 emissions (OECD, 2013). In addition, they also encourage investment in climate change mitigation technologies (Probst et al., 2021) and clearer consumption choices for all public and private spending, which can also future-proof investments (OECD, 2021).

Explicit carbon prices can either be set through a carbon tax, expressed as a fixed price per tonne of emissions, or through cap-and-trade systems, where an emissions reduction target is set through the issuance of a fixed number of permits, and the price is set in the market through supply and demand. In an emissions trading scheme or system, firms must remit allowances to cover their emissions. In essence, a government fixes the supply of allowances, and allowance trading establishes the emissions price.

In 2021 China opened the world's largest emissions trading market[31], covering 40% of its emissions, and 12% of global emissions, as part of drive to net zero by 2060. China will also use a declining cap to ensure emissions fall every year. At the time of writing there are 65 carbon prices schemes implemented in 45 national jurisdictions, representing some 21.5% of global GHG emissions[32]. However, the level is set nowhere near high enough: the average price of emissions worldwide is only around USD 2 per tonne, when a realistic level would be much higher. In the OECD framework for decarbonisation of the economy (OECD, 2022), it is evident that most countries under-price their carbon emissions.

Recently, vom Berg et al. (2021) have argued that a fossil carbon tax, i.e., a raw material tax, would be more efficient and simpler to implement than an end-of-pipe CO_2 emissions tax. In other words, taxing fossil fuels directly at extraction from the well may be more efficient.

The world's operating or developing carbon market schemes had a combined value of USD 272 billion at the end of 2021[33], including Europe, Canada, China, Japan, New Zealand, South Korea, Switzerland and the United States. There are essentially two methods for using revenues from these taxes to help grow the net-zero carbon economy. In the first, revenues are added to the general budget of a government, and that government can choose to use these revenues for climate-friendly purposes. Alternatively, the revenues can be legally earmarked or hypothecated for specific projects or purposes, rather than being added to the general budget. Both approaches have advantages: adding to the general budget minimises the cost for new administration, while earmarking is more direct, transparent, and perhaps easier to gain public acceptance (Marvik and Philp, 2020).

Tax revenue could be a cost-effective way to support long-term, higher risk research and more targeted short- to mid-term R&D, pre-competitive or near-market. There is also a case for the return of tax revenues to consumers in a 'citizen dividend'. Budolfson et al. (2021) found that revenues from carbon tax will be large enough to fund policies that can promote equality and relieve poverty. The choice is political, but judicious spending across a range of purposes is indicated.

Carbon tax is not a panacea

Carbon taxes target CO_2 emissions from fossil fuels. They do not directly target other carbon compounds like methane, which has a larger warming potential. Carbon emissions from many sources, such as agriculture, deforestation, waste management, and poor land use, are hard to assess and monitor and these are generally not taxed directly (World Bank, 2022). While most US policy schemes implicitly price such emissions in terms of CO_2 equivalents as part of full LCA assessment, non-tax-based policies would alternatively be needed to discourage emissions from sources like waste and farm management and land use practices.

A disadvantage of carbon taxes is that they may affect poorer people comparatively more than the more affluent. If the tax is accompanied by price rises, standard of living may drop, triggering unrest. Governments will need to consider if a phased increase in carbon tax would be favourable to mitigate unintended consequences. Coupling to less extreme but also less efficient measures, such as feebates and regulations, might improve public acceptability further due to their smaller or less direct impact on energy prices (IMF/OECD, 2021).

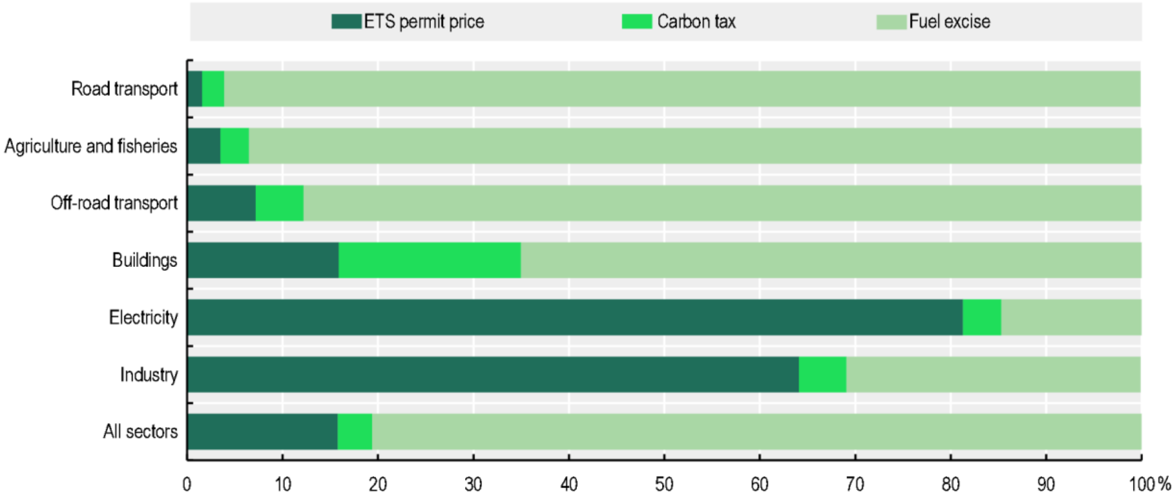
Strong, transparent and inviolable rules and regulations would be needed to make a carbon market work. Otherwise, emissions might even increase, and countries might 'double-count' their carbon saving efforts or take credit for low-carbon projects which would have happened anyway. Few carbon offsetting schemes are properly regulated, making the assessment of emissions reduction very difficult to measure and confirm. The burgeoning carbon offset industry has already been beset with doubts about the operational efficiency. Indeed, carbon offset schemes have been termed a "bookkeeping trick"[34], to obscure real emissions. West et al. (2023) examined the effects of 26 carbon offset project sites to reduce deforestation in six countries on three continents and found that most projects had have insignificant effects on reducing deforestation. For projects that did have effects, the reductions were substantially lower than claimed. This could lead to the conclusion that, in fact, offsetting to contain deforestation is failing (Jones and Lewis, 2023).

ETS versus Effective Carbon Rate

The ‘effective carbon rate’ sums carbon price, ETS and fuel excise. For different sectors the composition of effective rates is useful for a government to see how the system is working and where adjustments might be warranted. Figure 2.7 shows the effective carbon rates across the G20 countries in 2021.

Figure 2.7. The composition of effective carbon rates by sector, G20 economies, 2021

Percentage of total (%)



Note: G20 includes all the OECD countries and non-OECD Inclusive Framework jurisdictions that are members of the G20, except Saudi Arabia. Taxes are those applicable on 1 April 2021. The ETS price is the average ETS auction price for the first semester of 2021, except for China and the United Kingdom where it is based on information for the period in which they were operational (China: 16/07/2021, United Kingdom: 19/05/2021-30/06/2021) and the U.S. RGGI and Massachusetts and Tokyo subnational systems where, due to data limitations, the 2020 average was used. ETS coverage estimates are based on the OECD’s (2021), Effective Carbon Rates 2021, with ad hoc adjustments to account for recent coverage changes. Emissions refer to energy-related CO_2 only and are calculated based on energy use data for 2018 from IEA (2020), World Energy Statistics and Balances. The figure includes CO_2 emissions from the combustion of biomass and other biofuels. Carbon prices are averaged across all energy-related emissions, including those that are not covered by any carbon pricing instrument.
Source: OECD (2022), Taxing Energy Use 2022

In the electricity and industry sectors, emissions pricing mostly takes the form of emissions trading systems. In all other sectors, fuel excise taxes continue to dominate compared to explicit carbon prices. In buildings, there is a roughly even split between emissions trading systems and carbon taxes (OECD, 2021). The most relevant sector for this report is industry, and this could signal to governments that higher revenues might be more easily generated by improving the effective carbon rate through the carbon tax.

‘Carrot policies’ – building markets for renewable carbon

A level playing field is needed to include all economic sectors in all countries if net-zero carbon is to be achieved. However, this century has seen large and global policy action in energy and transportation, most prominent among the instruments being quotas and mandates for liquid biofuels.

It may not be surprising that the vast majority of public policy has been directed towards energy. Nevertheless, the mineral, chemical and material sectors account for the largest industrial sources of emissions, and it is now time for governments to focus here as decarbonisation of the energy and transport sectors is beginning to happen.

Production targets and mandates for renewable carbon fuels

Targets and mandates exemplify the different approaches to the introduction of biofuels in Europe and the United States. Incorporation targets (i.e., targets of percentages of biofuels blended into gasoline and diesel) have been approved voluntarily by several EU member states as national initiatives. The US biofuels policy has specified absolute production quantities through a mandate rather than a less-binding incorporation target (Ziolkowska et al., 2010). Mandates and targets for biofuels production have become standard for introduction of biofuels, and what follows may be partially or fully applicable to other low-carbon fuels such as CO_2 fuels.

Volume-based biofuels mandates provide certainty of demand within defined timescales, which gives the policy certainty that investors seek. They focus government support on certain technologies. Mandates are not without controversies and their application needs to be carefully thought through before deployment. A lesson from biofuels mandates is the need for countries to properly assess the technology pros and cons prior to unrolling market incentives such as mandates and to match them with focused technology-push policies. This way a country can match the technologies to its longer-term goals (Biofuture Platform, 2018). Conversely, if poorly chosen the selected mandated technologies may not provide the most cost-effective alternative to mitigate GHG emissions of the mandated sector(s) (Biofuture Platform, 2018).

In the European Union, ambitious blending mandates for sustainable aviation fuel (SAF) were recently agreed[35] as part of ReFuelEU Aviation (Box 2.6). Consistent with the IEA Net Zero 2050 scenario, the proposed mandates include not only bio-based fuels, but a progressing sub-mandate for synthetic fuels, i.e., fuels based on recycled carbon. This market stimulation scheme for SAF illustrate the importance of well-defined criteria for qualifying production pathways.

Box 2.6. European Union sustainable aviation fuel blending mandates

As part of the EU's "Fit for 55" package, the ReFuelEU Aviation blending mandates were agreed between the European Parliament and the European Council in April 2023, representing all 27 member states. This SAF policy, which is set to be implemented from 2025, will require airlines to use a minimum level of sustainable fuels for flights departing from EU airports. As part of the deal, airports will be required to ensure that their fuelling infrastructure is "fit for SAF distribution" (see Table 2.2).

The SAF mandate will start at a minimum of 2% share of SAF from 2025, rising to 70% by 2050 (Table 2.2). Moreover, there is a further requirement that a certain fraction of SAF should be synthetic fuel, i.e., based on recycled carbon defined by a set of detailed regulations. This sub-mandate will start at 1.2% in 2030, increasing to 35% in 2050. In other words, half of the SAF blending in 2050 should be synthetic fuels. At the time of writing, the step-up plan for synthetic fuel sub-mandates in 2040 and 2045 is not clear.

These blending mandates will require well-defined production routes. In addition to comply with a 70% emission reduction compared to a standard, there are further criteria related to allowed feedstocks. For instance, fossil CO_2 can only be used as feedstock for synthetic fuel (RFNBO) until 2041, after which the CO_2 should come from biogenic sources or DAC. The energy used, which in practice means hydrogen, should only come from renewable sources, implying that green hydrogen is accepted, while blue hydrogen is not.

It is noteworthy that a 20% blending mandate in 2035 would translate into a market demand of about 12 million tonnes of SAF in Europe alone. The fact that the current global capacity of SAF is only in the order of 300 000 tonnes illustrates the ambition level of this policy scheme.

Table 2.2. RefuelEU: Agreed mandates (April 2023)

Year	Overall SAF mandate	Synthetic sub-mandate
2025	2%	-
2030	6%	1.2%
2032	-	2%
2035	20%	5%
2040	34%	Unclear
2045	42%	Unclear
2050	70%	35%

Lapan and Moschino (2012) found biofuels production mandates to be more revenue-neutral than tax and excise reductions. They derived that an ethanol volume mandate is equivalent to a combination of an ethanol production subsidy and a fossil fuel (petrol) tax that is revenue neutral. They conclude that the (optimal) ethanol mandate yields higher welfare than the (optimal) ethanol subsidy.

An alternative to production mandates is based on carbon intensity, as used in the California Low Carbon Fuel Standard (LCFS), which sets annual carbon intensity (CI) standards. This approach is technology-agnostic, and the standard, or benchmark, decreases annually, with the intent of reducing the GHG emissions in transport by 20% in 2030. The policy effect in California is worth noting. About 60% of the market value of cellulosic ethanol is proving to be policy driven. This makes emerging biofuels with low carbon intensities cost-competitive with fossil fuels in the California market (IEA-AMF, 2020).

Stimulating markets for renewable carbon in chemicals

Public policy for reducing emissions in the mineral, chemical and material industries is a very different proposition compared to the energy sector. Energy has well-defined markets and regulation, and the number of fuels is small, while chemical and material products constitute tens of thousands. Thus, in these sectors obeying rules on carbon accounting, measurement and reporting is a much harder task than in energy.

A carbon intensity scheme would of course not work for carbon-based chemicals. Moreover, with tens of thousands of products, it is difficult to see how mandates or other support mechanisms used in the energy sector could be applied to renewable chemicals (Philp, 2015). Many aspects would be more complicated to assess, e.g., data gaps on real emissions savings, highly variable production pathways with different feedstock and energy inputs. Most of all, the bureaucracy behind mandating production of so many products would be most unattractive to the producers. However, a great many of the fossil products are manufactured via naphtha or a small number of platform chemicals such as olefins, hence a full LCA for the more limited number of key base chemicals may work in this sector.

Carus et al. (2014) described an innovative approach to the final problem above. As the biofuels market has now determined levels of GHG emissions savings for different categorisations, then it might be possible to describe an “ethanol equivalent”, from which other chemicals could be compared.

Green public procurement

Public procurement affects a substantial share of world trade flows. It accounts for 13% of GDP on average in OECD member countries (OECD, 2012). It is also being increasingly used to drive innovation and economic growth (OECD, 2019). Public procurement is a highly fragmented landscape: in the EU there are over 250 000 public authorities, and public procurement accounts for 14% of EU GDP (Núñez Ferrer, 2020).

Public procurers naturally tend to be very price-sensitive, which is a barrier for any innovative product. A real success story is the USDA BioPreferred Program[36], which specifically aims to increase the purchase and use of bio-based products. The programme has identified 139 categories of bio-based products (e.g., cleaners, carpet, lubricants, paints) and around 20 000 products for which agencies and their contractors have purchasing requirements.

There are broadly two main activities of the Biopreferred Program: mandatory federal purchasing and a voluntary labelling initiative (USDA, 2020). Providing a central product registry through an online catalogue enables purchasers to locate and compare products from all participating manufacturers, thereby encouraging them to compete to provide products with higher bio-based content.

More than 3 500 products have been approved to use the USDA Certified Biobased Product label (Figure 2.8). The programme partners with the ASTM International[37] (formerly the American Society for Testing and Materials) to ensure quality control and consistent results. This offers purchasers a universal standard to assess a product’s bio-based content.

Figure 2.8. The USDA Biopreferred voluntary label

Note: The capital letters FP appear on the label if the product is qualified for Federal Procurement.
Source: Courtesy of Andrew Jermolowicz, Director, Business Development Division, Rural Business- Cooperative Service, USDA Rural Development.

Policies to stimulate industrial symbiosis

Industrial symbiosis can be defined as[38] "the use by one company or sector of underutilised resources broadly defined (including waste, by-products, residues, energy, water, logistics, capacity, expertise, equipment and materials) from another, with the result of keeping resources in productive use for longer".

Stimulating cross-sectorial cooperation can assume many functions, including networking stakeholders, building resilient value chains, reducing capital needs, and consolidating the availability of resources and skilled labour. The main benefit of industrial symbiosis, however, may be energy optimisation, reducing overall cost, and the interplay between multiple applications of the same feedstock, reducing resource as well as business risk in the whole supply chain.

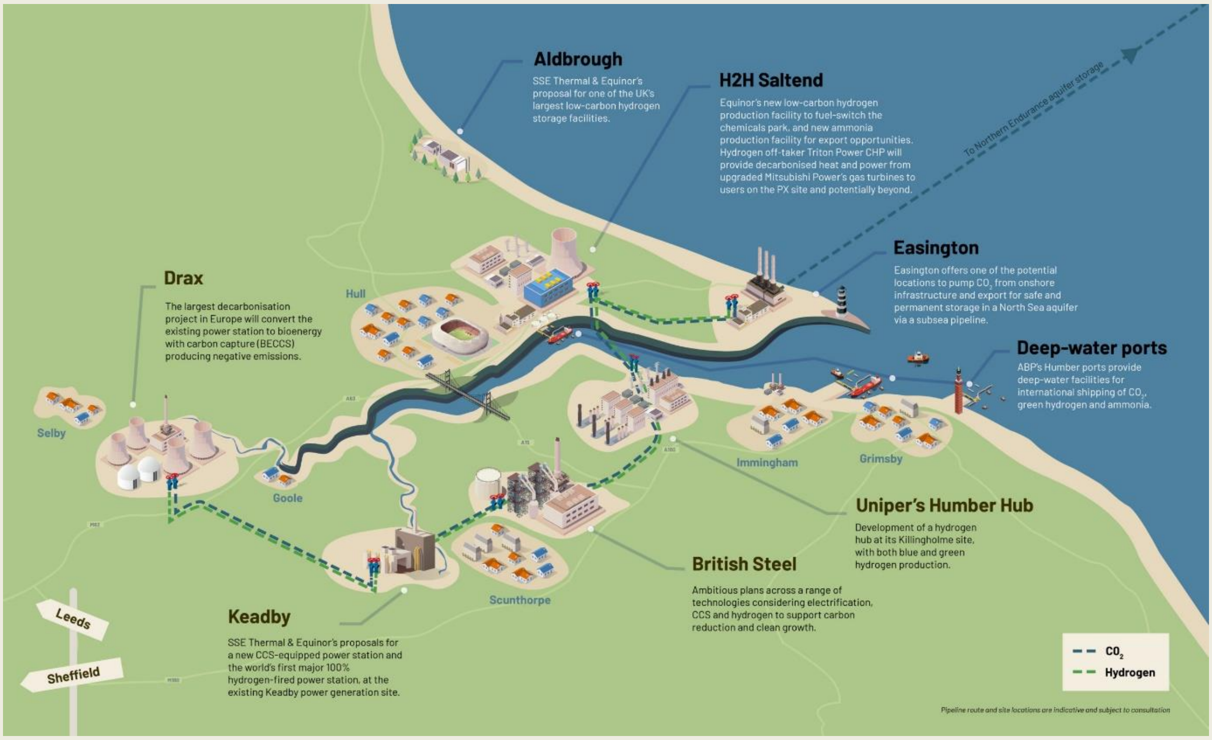
The concept is by no means new: as far back as at least 1997, the industrial ecology concept had been linked to decarbonisation (Erkman, 1997), but it can attract new impetus with the present policy focus on decarbonisation and carbon management. Perhaps the most famous example is the decades-old Kalundborg symbiosis in Denmark. At Kalundborg, waste, including physical materials but also heat, from one industrial facility becomes a feed to another.

While this is entirely consistent with the theory of the circular economy, Kalundborg is an example of a self-organised industrial symbiosis. A more deliberately planned model e.g., Zero carbon Humber, UK (Box 2.7, Figure 2.9) is integrated for carbon management and net-zero carbon planning. The planned model needs a conscious effort to identify firms and make them co-locate to share resources, therefore, it frequently involves at least one governmental agency.

Box 2.7. The proposed industrial symbioses at Humber, UK

A highly relevant example still under development is the UK Humber symbiosis, relevant because it encompasses CCS, hydrogen and BECCS (Figure 2.9). Its coastal location allows for sub-sea storage of CO_2 in the Southern North Sea. This is likely to be the exception rather than the rule as suitable sites for geological storage are limited. The location is described as the most carbon-intensive industrial region of the UK. For it to be viable in the future in the face of ever-tightening environmental legislation, CCS and clean hydrogen are most likely a necessity. Note that the plan accommodates “deep water facilities for international shipping of CO_2, green hydrogen and ammonia”. There are 14 formal partners, with public support from over 50 other international, national and regional organisations.

Figure 2.9. A schematic of what “Zero carbon Humber” might look like



Aldbrough

SSE Thermal & Equinor’s proposal for one of the UK’s largest low-carbon hydrogen storage facilities.

H2H Saltend

Equinor’s new low-carbon hydrogen production facility to fuel-switch the chemicals park, and new ammonia production facility for export opportunities. Hydrogen off-taker Triton Power CHP will provide decarbonised heat and power from upgraded Mitsubishi Power’s gas turbines to users on the PX site and potentially beyond.

Drax

The largest decarbonisation project in Europe will convert the existing power station to bioenergy with carbon capture (BECCS) producing negative emissions.

Easington

Easington offers one of the potential locations to pump CO_2 from onshore infrastructure and export for safe and permanent storage in a North Sea aquifer via a subsea pipeline.

Deep-water ports

ABP’s Humber ports provide deep-water facilities for international shipping of CO_2, green hydrogen and ammonia.

Uniper’s Humber Hub

Development of a hydrogen hub at its Killingholme site, with both blue and green hydrogen production.

British Steel

Ambitious plans across a range of technologies considering electrification, CCS and hydrogen to support carbon reduction and clean growth.

Keadby

SSE Thermal & Equinor’s proposals for a new CCS-equipped power station and the world’s first major 100% hydrogen-fired power station, at the existing Keadby power generation site.

Pipeline route and site locations are indicative and subject to consultation

Source: Zero carbon Humber: www.zerocarbonhumber.co.uk/

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3

Holistic innovation policy

The complexity of carbon management in terms of the range of economic sectors and the developing technologies suggests that applying policy to only a single part of a value chain or ecosystem of actors is likely to cause knock-on effects elsewhere. In holistic policy formulation, the core policy problems that tend to afflict the activities of innovation systems are identified, including the unintended consequences of policy itself. It is especially important due to the need for a range of both technology-push and market-pull policies.

Carbon transition policies needs whole society engagement.

> *"The Climate Change Committee (CCC) has indicated that the majority (~62%) of emission reductions will require some form of societal and behaviour change including the adoption of low-carbon technologies and changes to the way we live our lives".*
>
> *Demski, 2021*

The green transition comes at a price but with disproportionately high benefits

The decarbonisation of large-scale centralised electricity generation is a major success story of decarbonisation. To reach net zero, however, more far-reaching reductions in carbon emissions are required, some of which will impinge much more on people's lives. Behavioural change desired by governments is always controversial. What might be expected in these behavioural changes are, for example, modifying diets to food sources that are low in emissions, reducing food waste, taking fewer flights and mobilising more mass transport.

As argued previously, the urgency calls for strong and decisive policies. However, measures that are too extreme (and too many) may lead to economic instability and social disruption. Significant challenges will exist for firms that have to change their business models and for workers that are displaced. Skill sets will evolve and here adult skill provision and lifelong learning will be needed for labour market resilience and to meet the evolving demands for competence (Hodgson et al., 2022).

A lack of public support may prevent the implementation of necessary but, in the short term, difficult measures. As seen in recent years, energy controversies have led to significant social unrest in various locations. With internet and the new tools of social media, societal protest and peaceful demonstrations can be organised much more quickly. Unfortunately, a more disturbing aspect of social media is that it can also be used for disinformation[1] or potentially foment forceful riots.

Gilmore and Buhaug (2021) isolated the effects of climate policies on economic performance, income and livelihood, food and energy prices, and land tenure as the four most likely factors to increase conflict risks. Governments need contingencies to tackle the spectre of energy and commodity price rises that may arise in the transition to less efficient (more expensive) carbon feedstocks. Moreover, the public may not appreciate the more long-term job creation potential of carbon management strategies, while job losses from traditional fossil industries will be immediately apparent.

Along the way social acceptance must be secured. Governments and intergovernmental processes need to invest strongly in communication with the general public and innovate in ways for civil society engagement and education. Channels such as television, social media and targeted community meetings work quickly to reach a large proportion of the population.

There are sharply divergent parties involved and vested interests that are opposed to net-zero carbon. There is not a lack of information, but there is a lot of bad information. To secure credible information there is a need for innovation in institutions capable and willing to disseminate information that is informative and trustworthy. To raise awareness of the geopolitical ramifications that lie ahead, the International Renewable Energy Agency (IRENA) established the Global Commission on the Geopolitics of the Energy Transformation[2], with the support of the Governments of Germany, Norway and the United Arab Emirates (IRENA, 2019).

Definitions and terminology facilitate communication

Definitions are necessary in any economic activity to gather data that are comparable across regions, countries and globally. Ultimately, integration of actors across sectors and hence the creation of new value chains is limited by disparity and lack of control of terminology and standards. In short what is called for is *commonly agreed vocabulary throughout value chains, from feedstock suppliers to downstream actors in the application sectors*[3]. Different definitions and pathways to net-zero can have drastically differing outcomes.

Olfe-Kräutlein et al. (2022) pointed to how the inconsistencies in meanings in the current use of terms like CCU, CCUS and CDR have consequences for a variety of stakeholders in industry, policy making, and the public more generally. Policy makers should be aware that even if the expert community perceives little problem, the attitude of the public towards a technology can be greatly influenced simply by its name. The conflation of CCU and CCS in the term CCUS can be particularly problematic. The main value of the paper by Olfe-Kräutlein et al. is that it sets out the problems and potential solutions in a single document. They also direct the reader to glossaries that intend to work towards a common terminology. Of particular relevance to this report is a glossary developed by the International CCU Assessment Harmonization Group[4].

Raising awareness and public acceptance

Communication is vital for public acceptance: up to 70% of the potential of the "Bio-Revolution" may depend on consumer, societal, and regulatory acceptance (McKinsey Global Institute, 2020). From a wider societal perspective, local decision-making, and delivery mechanisms, such as Citizens' Assemblies[5], can help generate policies and projects for sustainable growth that are seen as fair and focused on local needs and perspectives.

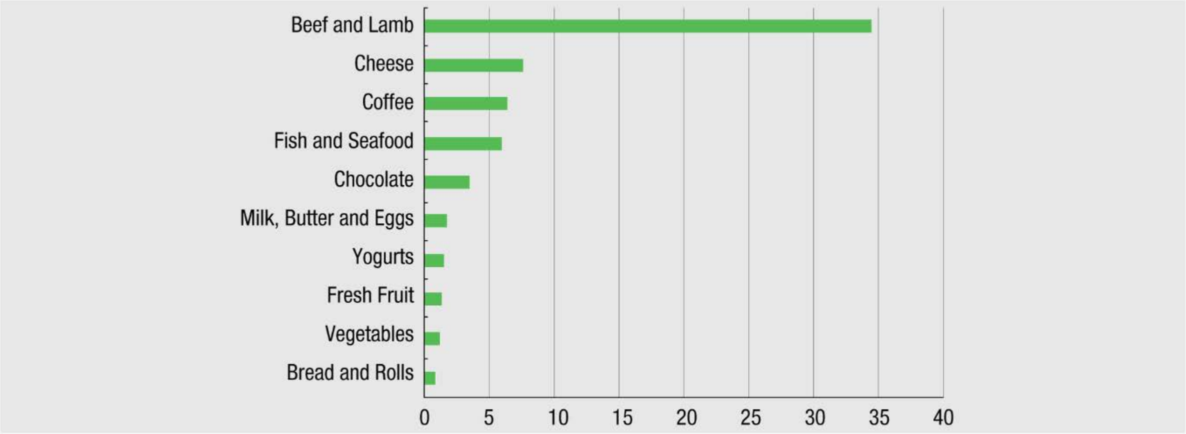
One of the keys to public acceptance is job creation. Recent analysis by Montt et al. (2018) concluded that most economies will experience net job creation in the transition to a low emission society. Governments must find effective ways to communicate such messages, for instance by allying these 'green' jobs to a paradigm of policy certainty and permanence.

For sectors such as chemistry and cement, the difficulties in raising awareness are exacerbated by a lack of customers. Some of the carbon-based sectors are mainly business-to-business models. Chemistry is an exemplar B2B sector. In contrast, production of food or clothing has a distinct advantage due to the communication power of large supermarkets and the much greater familiarity of the public with the products. Hence, there is some tentative evidence that consumers want to make decisions on the environmental sustainability of foods (e.g., UK Food Standards Agency, 2021). Eco-labelling of foods, however, tend to focus on a single factor that may or may not be related to sustainability.

An algorithm-based tool is under development that can assess the environmental impacts of 57 000 foods based on four indicators: GHG emissions, land use, water stress, and eutrophication potential (Clark et al., 2022). Aware that consumers are likely to prefer a simple eco-label, the researchers devised a single estimated composite environmental impact score per 100 g of product ranging from 0 (no impact) to 100 (highest impact) (Figure 3.1).

Figure 3.1. Composite environmental impact of some common foods based on four indicators

Abscissa: the composite environmental impact figure – higher the figure, higher the environmental impact



Source: Derived from data provided by Clark et al. (2022) under Creative Commons Attribution License 4.0

What is clear from such an analysis is that it would need to be more refined to take account of a particular production pathway. For example, beef produced locally within a short distance of a supermarket will have a different environmental impact than beef frozen and transported long distances by sea. Nevertheless, this might represent a first step towards an eventually standardised food sustainability eco-label that integrates emissions information with other sustainability indicators. And if the algorithm can deal with 57 000 different foodstuffs, then perhaps the 70 000+ products of the chemicals industry may not be so daunting. This could be a method to directly compare identical 'drop-in' fossil-based and renewable-based products, data vital to establishing realistic sustainability comparisons.

In the largest survey of public opinion on climate to be conducted to date (UNDP, 2021), the top three policies voted for among the 1.2 million people surveyed were: conservation of forests and land; deploying solar, wind and renewable power, and climate-friendly farming techniques. A recent survey (Cox et al., 2020) sampling populations in the United Kingdom and the United States showed that very few people believed that carbon dioxide removal (CDR) deals with the root cause of emissions. This echoes a recommendation in this report that policy for technologies such as CCS should not obscure the need for genuine low emissions technologies (and, in consequence, for supportive policy).

Cox et al. (2020) discovered in their study that engineered CDR risks a failure to achieve a clear social licence to operate if revealed dilemmas cannot be properly resolved. These dilemmas are entwined with questions regarding the relationship between emissions reduction and carbon removal as means for achieving net zero. It can be expected from their findings that many citizens perceived CDR as a form of 'dumping' rather than contributing to sustainability.

Furthermore, they used an approach of 'deliberative workshops' to give participants an extended period to form their opinion because of demonstrably low prior awareness, which can dramatically impact responses to surveys. Low prior awareness can be a deciding factor in public debate over new or emerging technologies.

Public engagement needs innovation in approach, and it will need to be consistent and long-term. Moreover, an effective public engagement strategy should encourage active participation in decision making. It will be a strategy of joined-up measures including communication strategies, stakeholder engagement, participatory mechanisms, and behaviour change (Demski, 2021). Methods need to not only measure responses across a population, but also reveal why people respond in a certain way. The OECD described twelve different forms of deliberative public engagement with examples from across the world (OECD, 2020).

Carbon management as an overarching framework for policy making

As argued in previous chapters, carbon management provides a more holistic understanding of carbon-based value chains. Moreover, the case studies, workshops, as well as input from national delegates, document how carbon management can serve as an improved basis for policy making. In this chapter a guide to integrated carbon policies is proposed through a framework familiar to innovation policy makers: the combination of supply- and demand (market-making) measures and those that apply to both. These measures are summarised in Table 3.1. Subsequently, such policies should be aligned with more general policies, for example macroeconomic policy, to show how the shocks of net-zero measures may be ameliorated through interaction (Table 3.4).

Table 3.1. The supply- (feedstock/technology push) and demand-side (market pull) measures typical of science and technology policy

Feedstock/Technology push	Market pull	Cross-cutting
Local access to feedstocks	Targets and quotas	Standards and certification
International access and trade of feedstocks	Mandates and bans	Techno-economic analysis
R&D subsidy programmes	Public procurement	Skills and education
Pilot and demonstrator support	Direct financial support	Regional clusters
Flagship financial support	Tax incentives	Definitions, terminology
Tax incentives for industrial R&D	Incentives related to emissions	Governance and regulation
Improved investment conditions	Taxes on fossil carbon	Raising awareness
Innovation clusters	Fossil fuel subsidy reform	Public deliberation

Source: Adapted from OECD (2018)

Borrás and Edquist (2019) examined the following components for the formulation of holistic innovation policy: knowledge production and research and development; education, training, and skills development; functional procurement as demand-side measures; change of organisations through entrepreneurship and intrapreneurship; interaction and innovation networks; changing institutions and regulations; and the public financing of early-stage innovations. Many of these aspects are directly relevant to innovation for carbon management.

The need for policy coherence can be seen in the future of plastics as an example. Sustainable production and use of plastics involves new feedstocks, e.g., bio-based chemical building blocks and more renewable energy input, but also changes in product design and manufacturing to allow for mechanical and chemical recycling, infrastructure and policy for collection and separation, and even changes in consumer behaviour.

Policy coherence is not easy as it requires a high level of inter-ministerial coordination. However, it is necessary to avoid inconsistent policy (e.g., a waste in an environment ministry could be a secondary raw material in an industry ministry). Furthermore, expensive investments in redundant or near-sighted infrastructure may create lock-in situations, e.g., if a national strategy is legally set for the expansion of waste incineration, this prevents initiatives in mechanical or chemical recycling.

To illustrate the point, plastics policy in Europe is linked to at least the following other very important European policies, as well as to the UN Sustainable Development Goals:

- European Green Deal (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en)
- Circular Economy Action Plan https://ec.europa.eu/environment/strategy/circular-economy-action-plan_en#:~:text=The%20new%20action%20plan%20announces,for%20as%20long%20as%20possible)
- European Industrial Strategy (https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age/european-industrial-strategy_en)
- Chemicals Strategy for Sustainability (https://echa.europa.eu/hot-topics/chemicals-strategy-for-sustainability)
- Zero Pollution Action Plan (https://ec.europa.eu/environment/strategy/zero-pollution-action-plan_en)
- Biodiversity Strategy to 2030 (https://ec.europa.eu/environment/strategy/biodiversity-strategy-2030_en)

Complexity sets the scene for policy dilemmas and unintended consequences

For policy makers the questions posed, and the policy dilemmas entailed in sustainability and carbon management are complicated and will inevitably result in compromises and trade-offs. Some overarching policy dilemmas were already identified in Chapter 1:

- Intensified use of bioresources and land use change may lead to biodiversity loss. For example, the use of land to make biomass feedstocks for, say, bioplastics production could easily compete with food production (Rosenboom et al., 2022). In a ‘planetary boundaries’ analysis of the future of the petrochemicals industry by Galán-Martín et al. (2021), the scenario with the lowest carbon footprint in a renewable carbon transition could exceed the biodiversity planetary boundary by at least 30%.
- CCS may slow down innovation and more profound societal and industrial changes, especially if these changes delay genuine low-emissions technologies (Stephens, 2014). This is highlighted as a policy action for policy makers. There is a danger that policy makers make CCS the *de facto* technology, sending signals to industry to continue ‘business as usual’ in the knowledge that CCS is the ‘forever’ technology that inhibits investment in truly low-emissions technologies.
- CCU and DAC require huge amounts of renewable energy, competing with energy needs and electrification of other sectors, such as transportation or domestic heating. Furthermore, to make CCU technologies justifiable, it would be necessary to use renewable energy as the energy source and may compete with other important energy requirements.
- Saygin and Gielen (2021) predicted that deep emissions reductions are possible in the chemical industry by mid-century, but they estimate that product cost may rise by 35% compared to today. As chemistry is virtually ubiquitous in modern manufacturing, how will this be received by society? They estimate that investment needs amount to USD 4.5 trillion between now and 2050. Governments will have an essential role in enabling this transition, but will there be the public and political will to do so?

History is replete with detrimental unintended consequences of well-meaning policies, often leading from too great a focus on intended consequences (Ehrlinger and Eibach, 2011; Herrero et al., 2020). As examples:

- Environmental regulations to preserve wilderness and wildlife can paradoxically result in increased GHG emissions (Severnini, 2019).

- In order to prevent marine pollution and dumping of waste at sea, the London Convention from 1972 (formally the ‘Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972’) and its update in 1996, the London Protocol[6], enforces restrictions on marine and cross-border transport of CO_2. This has caused problems for current CCS ambitions, for instance the Norwegian Longship project[7].
- Also, the discouragement of plastics in food packaging to reduce pollution may negatively affect food distribution and self-life.

Thus, a further complication for holistic, systemic policy development is that efforts should be made to identify and model the most likely trade-offs involved - or, as expressed by Kotchen (2018), “offsetting goods and bads”.

A promising approach is to couple supply chain models to feedstock conversion models (De Buck et al., 2020; Ulonska et al., 2018). As pointed out by De Buck et al., the sustainability and economic feasibility of a biorefinery feedstock supply is as important as the engineering process. Ulonska et al. added other factors, such as market-dependent price developments and design and sustainability, to model “*all main influencing factors*” simultaneously. Similarly, Jonkman et al. (2019), designed a decision support tool for the sustainable design of a biorefinery supply chain network that included all local actors.

An approach that is likely to find favour with policy makers is to couple trade-offs (and co-benefits) to the UN SDGs:

- This would give a framework for international comparability, as the SDGs were adopted by all United Nations member states.
- The analyses will endure as the SDGs are part of a 15-year plan, coming to a conclusion at the critical juncture of 2030.
- The SDGs in theory cover all sectors of human activity, thus lending an aspect of universality.
- The SDGs should be applied in a manner that seeks synergies with other goals to prevent sector silos from creating barriers.

Box 3.1 demonstrates the utility of this approach that analyses bioenergy contributions to the SDGs.

Box 3.1. Contribution of biomass supply chains for bioenergy to sustainable development goals

Blair et al. (2021) adopted a scoring framework devised by Nilsson et al. (2016) to examine how biomass used for bioenergy applied to SDG target 7.2 interacts with other SDGs. The methodology may be adaptable to other sectors and targets than bioenergy if data are available.

The system has positive and negative scored interactions ranging from +3 to -3. A positively scored interaction represents opportunities for synergies and perhaps co-benefits, while a negatively scored interaction would indicate the need for actions to prevent trade-offs (Table 3.2).

Table 3.2. Scoring framework developed by Nilsson et al. (2016)

Interaction	Score	Explanation
Indivisible	+3	Inextricably linked to the achievement of another goal
Reinforcing	+2	Aids the achievement of another goal
Enabling	+1	Creates the conditions that further another goal
Consistent	0	No significant positive or negative interaction
Constraining	-1	Limits options on another goal

Note: The four supply chains used in the analysis by Blair et al. (2021) were: forest biomass, agricultural residues, energy crops and waste of biological origin e.g., the organic fraction of MSW.
Source: Blair et al. (2021).

Singling out SDG 12 and the targets indicated in Table 3.3 below, a matrix of scores indicating a category of consequence (enabler, driver/co-benefit or safeguard) can be obtained. “Safeguard” indicates the need for attention to potential trade-offs, which are described in the final column.

To inform the assessment, each analyst relied on a broad range of synthesis papers, modelling studies, and empirical analyses of bioenergy and biomass supply chains. Thus, the work requires expert knowledge and it not without difficulty, but the results form an analytical, if still qualitative, approach to determining interactions.

Table 3.3. Scoring of synergies and trade-offs between target 7.2 and SDG 12

SDG	Target(s)	Linked with	Score	Category	Interaction identified
12 Sustainable Production and Consumption	Political support	All-supply	+2	Enabler	Bioenergy may be supported as part of national sustainable consumption and production plans, or by other policies supporting sustainable business practices or procurement programmes.
	Knowledge and capacity building	All	+1	Enabler	Improved education and awareness surrounding sustainable consumption, and improved technological capacity may advance bioenergy, particularly in developing countries.
	Sustainable, efficient use of resources	Forest/ Ag. residue	+2	Driver/co-benefit	Use of residues for energy results in more efficient use of resources, and lower material footprint than extracting and burning fossil fuel, especially if residue previously unused or burned.
			-2	Safeguard	If removal of residues is too intense, it may reduce soil quality or crop/forest productivity, and inputs of fertilizers and material footprint may increase. Fibre may be diverted from higher priority uses, e.g., food, construction materials.
	Waste generation, treatment	Waste	+1	Driver/co-benefit	Potentially hazardous waste streams can be diverted/captured to generate energy. Waste to Energy (WTE) may increase the recovery of metals.
			-1	Safeguard	Digestate, generated via anaerobic digestion of waste streams can impact the environment if not treated properly. If waste is used for energy, there may be less incentive to improve recycling.

Note: Target 7.2 is: “increase substantially the share of renewable energy in the global energy mix”.
Source: Adapted from Blair et al. (2021)

In holistic policy formulation, the core policy problems that tend to afflict the activities of innovation systems are identified, including the unintended consequences of policy itself (Borrás and Edquist, 2019). The interdependency of different carbon feedstocks, integrated processing of side streams and cascading use, all emphasise the importance of a holistic approach to carbon-based value chains. If an understanding of these complex interactions is lacking, policies may fail to deliver on their sustainability objectives. Conversely, building a holistic policy framework is more likely to succeed with fewer unintended consequences than treating policy questions in isolation[8].

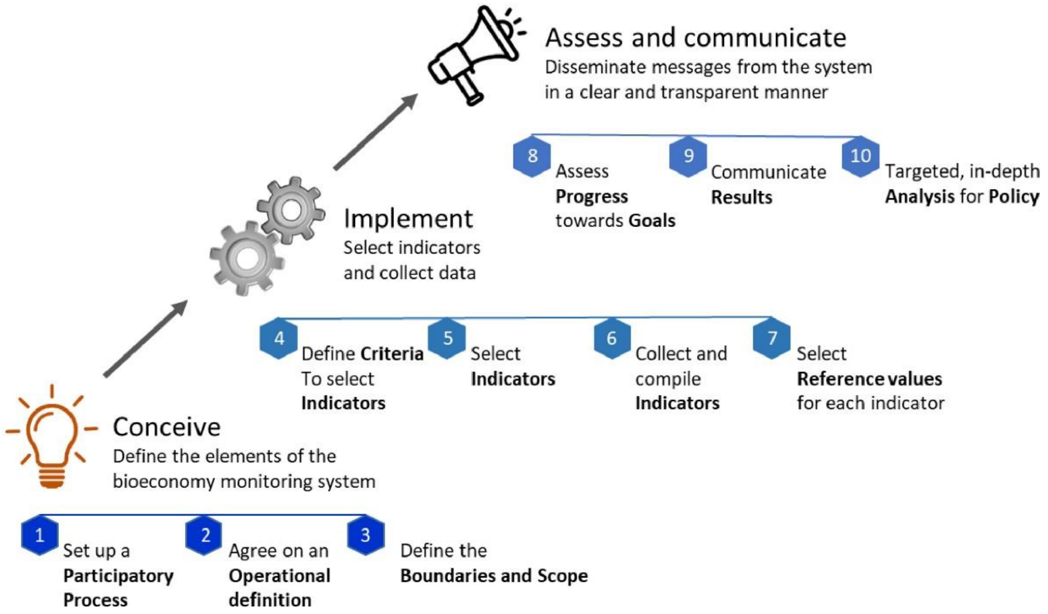
Governance and regulation

OECD analysis suggests that innovation heavily depends on issues of governance and implementation (OECD, 2015). Governance matters in innovation policy due to the various levels of authority and policy competencies involved. Budgetary resources are distributed across various levels of government when horizontal policy is created. Regionalisation and decentralisation have made regional and local governments more powerful and has increased their capacity to operate their own development strategies.

It is worth noting that in many areas, governance frameworks are already in place. The chemicals and materials are for instance governed by REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals)[9] in Europe and by TSCA (Toxic Substances Control Act, 1976)[10] in the United States. A main new paradigm would be to adopt sustainability as a mode of governance, reinforcing the need for rational measurement of sustainability.

A robust knowledge base and a fit-for-purpose monitoring system are crucial elements for adaptive and effective governance. The Joint Research Centre of the European Union is developing an approach to bioeconomy monitoring along the entire value chain. The system consists of ten steps to monitoring and evaluation (Figure 3.2), with the selection, collection and compilation of indicators at its core, along with selection of reference values for each indicator. Such an approach could also be adapted to renewable carbon processes outside the bioeconomy.

Figure 3.2. Ten steps to monitoring and evaluation of the bioeconomy



Source: Adapted from De Santi (2021)

Regulation refers to the implementation of rules by public authorities and governmental bodies to influence the behaviours of private actors in the economy. Within innovation policies, the primary purpose of regulation should be to stimulate innovation, although the opposite is undeniably possible. Complex and time-consuming regulation is far more damaging to small companies than it is for large companies. Regulatory barriers take a variety of forms, two of the most relevant (Sira Consulting, 2011) are:

- *Fundamental constraints.* These call for a political and policy approach (e.g., import duties, level playing field, certification of products, and financial feasibility).

- *Operational constraints.* Here the regulation itself is not the problem but its implementation by, for example, local authorities. Especially for SMEs, these lead to substantial barriers to investment.

Putting the framework together: being systemic

It is recognised that public supply-side investments may not be sufficient to drive technology deployment if the market conditions are not favourable. Higher cost and market acceptance are particular challenges in the immature markets based on renewable carbon. Hence, there needs to be a balance of supply- and demand-side measures, and this balance should be calculated in advance, and the policies timetabled.

Policy must address systemic business risks in value chains

A value chain can be defined as "a set of interlinked activities that deliver products/services by adding value to bulk material (feedstock)" (Lokesh et al., 2018). Typically, many of these individual processing and manufacturing steps are new and untried and various public and private actors need to work together to create new industrial ecosystems. The complexity of the renewable carbon web can easily be underestimated, resulting in, for example, unforeseen shortages of critical material(s) (National Academies of Sciences, Engineering, and Medicine, 2020a).

In general terms, Hellström (2003) described "'negative synergies' between complex technologies, social institutions and critical infrastructures". A CCU value chain would typically comprise a cascading series of manufacturing processes, spanning feedstock production/capture, pre-treatment, and conversion, through to the manufacture and marketing of products (and in the case of some products like plastics, even end-of-life). Thus, the new value chains created are characterised by an interdependency between multiple stakeholders. Getting them to work efficiently is threatened by 'systemic business risk'. Such systemic risk discourages investments and in the early phases of this transition must be addressed by policy (as the markets may not be ready).

A supply or value chain is only as strong as its weakest link (Jażdżewska-Gutta and Borkowski, 2022). Despite large potential for societal benefits, a single failure in the value chain might have the overall effect that the system will not work technically, logistically or financially (Marvik and Philp, 2020). In other words, if policy simply acts on individual parts of a complex industrial system, then there is a substantial risk of wasted resources and effort. This underscores the need for coordination of different policy families along value chains, as well as across disciplines and sectors (Weber and Rohracher, 2012).

Systems thinking in sustainability policies

A critical 'sustainability system' is land use. Replacing a major part of current fossil carbon demand with fresh biomass will put huge pressure on agriculture and forestry. Shortage of arable land, water and fertilizers have already led to conflicts between different sustainability goals (D'Amato et al., 2017) related to, for instance food, energy and biodiversity and major concerns from associated land use change and deforestation (Searchinger et al., 2018).

One would expect policies to prioritise the use of renewable carbon in those value chains where no alternatives are available, e.g., food, chemistry and materials, while in fact, public policy attention has mainly been directed towards bioenergy. This indicates a need to better balance the policies (Philp, 2015), in consideration of potentially conflicting sustainability goals. This balance needs to take account of the fact that biomass can achieve multiple goals, as enshrined in the cascading use of biomass.

Dietz et al. (2018) identified the political management of conflicting goals as one of the major challenges for a sustainable bioeconomy governance framework. While it is generally agreed that human primary needs, such as food security, have to be prioritised in the bioeconomy, food production *per se* is typically not the major cause of malnutrition and famine; but rather inefficiencies in food management, distribution and wastage (Berners-Lee et al., 2018). This is an illustration of the complexity to be tackled in the green transition, and highlights the possibilities of unintended consequences, reinforcing the need for a holistic approach.

Innovation policies should incorporate a time dimension

Table 3.1 may have limited utility as it does not imply a temporal strategy and a progression path for policy makers, i.e., it lacks any conception of a sequence of policy implementation. Marvik and Philp (2020) refined the approach by describing the mix of specific and general measures in a widely accepted innovation policy sequence from ‘ideas to market’ (European Commission, 2020; World Bank Group, 2020), an approach familiar in other sectors e.g., energy (IEA, 2009) and nanotechnology (Lim et al., 2015).

A bioeconomy-specific version of the four-step matrix shown in Table 3.4, was used to develop the Norwegian national bioeconomy strategy (Ministry of Trade, Industry and Fisheries (Norway), 2018). It may give policy makers a broader idea of how to construct a strategy that will connect supply- and demand-side drivers to achieve a stronger and more robust effect on the economic system. Specifically, this matrix may guide different ministries and agencies to know when and where their roles are required, or how and when they need to work together.

Finally, as referred to several times, increases in prices for basic commodities can cause price and inflation hikes. Therefore, a connection to macroeconomics is inevitable, where classical mechanisms like price subsidy reform (IMF, 2000) and central bank control of inflation to the desired levels are triggered.

Table 3.4. A net-zero carbon innovation policy framework

Feedstock	Technology	Industrialisation	Market
Objectives			
Stimulate availability of resources	Strengthen skills and technology base	Trigger investments in new manufacturing	Increased sustainability and value creation
Value chain specific policies			
Resource regulations and permits	Targeted R&D grant programmes	Public technology scale-up and pilot facilities	Product standards and norms
Transportation and logistics infrastructure	Specific education and training programmes	Financial support for flagship projects	Price subsidies and product tax policies
Feedstock specific trade regulations	Technology cluster and network support	Targeted government investment programmes	Product mandates and bans policies
Generic policies			
Feedstock sustainability assessment studies	Broad scope R&D grant programmes	Start-up and SME support	Sustainability labels and communication
Governance and regulation efficiency	Tax incentives for applied R&D	Industry-oriented education programmes	Public awareness and acceptance campaigns
Waste management policies	Stimulate international partnerships	Techno-economic feasibility studies	Tax on CO_2 emissions and fossil fuel subsidy reform
International trade agreements	Exchange programmes and apprenticeship	Private investment stimulating policies	Public procurement of renewable carbon products
Connect to macroeconomics			
In the event of high food and energy prices: price subsidy reform, central banks control inflation to desired levels through the interest rate mechanism or money supply			

Source: Adapted from Marvik and Philp (2020)

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4

Carbon management technologies

This chapter seeks to illustrate the importance of technological development in carbon management. It is worth noting that while most technologies have some relation to climate action, the perspective presented here is much broader and consistent with the message of avoiding ‘sustainability tunnel vision’. It will be apparent that there is very large scope for ‘hybrid’ technologies, involving more than one type of technology, such as a combination of bio- and nano-technologies.

While classic biological production is indispensable for most food and feed, fibres and other complex molecules like performance chemicals and biopharmaceuticals, the chemicals industry could concentrate more on CO_2 as a feedstock (Carus et al., 2020), despite the thermodynamic difficulties of doing so, using hydrogen as a supplementary reagent and energy carrier. The synthesis of simple organic chemicals and fuels are amenable to new processes based on biotechnological (e.g., gas fermentation), new strategies for chemical synthesis and nanotechnology. All of this would relieve pressure on land and increase circularity, major goals for sustainability.

In the following sections, various technologies are described through their potential application and impact, rather than the technologies *per se*. Table 4.1 attempts to categorise some of the technologies described, both by the energy/land use system they affect and the SDG(s) that they address. As alluded to above, governments tend to pick out wanted consequences, while governments must also be alert to the unwanted.

In this description, revisiting the key value chains of bioproduction (i.e., the bioeconomy) is the start-point, followed by the new alternatives to carbon-based products, such as recycling of carbon and direct air capture of CO_2. This also includes a description of technologies involved in hydrogen production, as hydrogen is increasingly an essential reagent in carbon-based value chains. Finally, the development of carbon capture and sequestration is outlined, being perceived to be essential for managing overshoot and unavoidable emissions.

Table 4.1. Technologies described and their relation to energy/land use system and SDGs

Technology	Energy/Land use system		SDGs	
	Primary	Other	Primary	Other
N-fixing cereal crops	Agriculture	Waste	2	3, 6, 10, 13, 14, 15
Ammonia	Agriculture	Industry, Transport	2	7, 9, 12, 13, 15,
Soil	Agriculture	Forestry, Waste	2	3, 10, 12, 13, 15
Chemical recycling	Waste	Industry	12	6, 9, 11, 13
Anaerobic digestion	Agriculture	Power, Waste	7	11, 13, 15
Methanol	Industry	Transport	12	8, 7, 8, 9, 13
DAC	Power	Industry	13	8, 9, 12,
Wood in construction	Forestry	Buildings	11	9, 12, 13, 15
Cement/concrete	Buildings	Waste, Mining	11	12, 13, 15
BECCS/DACCS	Power	Industry, Transport, Forestry, Waste	7	8, 9, 12, 13
Nanotechnology	Industry	Power, Transport, Buildings, Agriculture, Waste	12	3, 4, 6, 7, 8, 9, 11, 12, 13, 15
Synthetic biology	Industry	Transport, Agriculture, Waste	12	2, 3, 4, 6, 7, 8, 9, 11, 13, 14, 15
Synthetic chemistry	Industry	Power, Transport, Buildings, Agriculture, Waste	12	3, 4, 6,7, 8, 9, 11, 13, 14, 15

Note: Energy/land use systems: power, industry, transport, buildings, agriculture, forestry, and waste.
SDGs goals: 1: No Poverty, 2: Zero Hunger, 3: Good Health and Well-being, 4: Quality Education, 5: Gender Equality, 6: Clean Water and Sanitation, 7: Affordable and Clean Energy, 8: Decent Work and Economic Growth, 9: Industry, Innovation and Infrastructure, 10: Reduced Inequality, 11: Sustainable Cities and Communities, 12: Responsible Consumption and Production, 13: Climate Action, 14: Life Below Water, 15: Life on Land, 16: Peace and Justice Strong Institutions, 17: Partnerships to achieve the Goal.
BECCS and DACSS differ in that BECCS involves providing clean energy, while DACCS is purely storage and requires clean energy.

A fresh look at bioproduction

A fresh look at bioproduction is meant to reflect the realisation that biomass and bio-based production cannot replace all fossil-based production in a manner that would preserve other sustainability necessities, such as biodiversity.

Projections suggest that more than 840 million people worldwide will be undernourished by 2030. By century end, some 10 billion people will need carbon-neutral food systems that are resilient to extreme weather and resistant to current and emerging pathogens while respecting planetary boundaries (Fraser and Campbell, 2019).

In fact, some of the most significant challenges in climate change relate to agriculture. Agriculture, forestry and other land use (AFOLU) activities accounts for around 23% of total net anthropogenic emissions of GHGs (IPCC, 2020). Environmental damage caused by the food system could increase by 50-90% by 2050 if technological change and dedicated mitigation measures are not deployed (Springmann et al., 2018).

Attempts to improve crop yields by conventional plant breeding over the last 50 years or so have been characterised by an improvement of about 1% per year (Foyer et al., 2017), while what is probably needed as a year-on-year improvement to 2050 is 1.7%. One promising way to achieve such a step increase is to improve the efficiency of photosynthesis (Kromdijk et al., 2017).

Photosynthesis is the primary determinant of crop yield (Simkin et al., 2019), but the maximum overall photosynthetic efficiency of plants is only 3-6% of total solar radiation and in practice considerably lower. Given the relatively slow progress in crop yield improvements, de Souza et al. (2022) described a remarkable improvement in a bioengineered strain of soybean. In replicated field trials, they increased photosynthetic efficiency and seed yield by up to 33% without a decrease in protein or oil content.

Biotechnologies coming of age

In the landmark OECD bioeconomy publication (OECD, 2009), biotechnology was envisioned to be the backbone of the emerging bioeconomy. While developments in biosciences and capabilities in bioengineering have been tremendous, biotechnology is still far from reaching its full potential as an enabler of sustainable bio-based production. However, many examples of an increasing impact are visible.

- *Breeding for climate resilience.* One important area is genomic selection of crops with enhanced ability to grow under multiple climate-related stress conditions (Budhlakoti et al., 2022). This could be especially important in the future regarding resilience to drought and high temperatures. For example, recently CRISPR tools have been effectively applied to elucidate drought and saline environments tolerance mechanisms in plants (Shelake et al., 2022).
- *Pest-resistant genetically engineered crops* (Tabashnik and Carrière, 2017). Some plant pathogens have already expanded their host range or distribution, at least partly as a result of climate change (Gullino et al., 2022). It is considered that genetically engineered crops can be critical components of an integrated pest management (IPM) plan in both developed and developing countries (Anderson et al., 2019).
- *Increased nutritional value.* Paine et al. (2005) described a strategy to increase the nutritional value of golden rice through increasing the pro-vitamin A content. Other target crops for biofortification are among the most important globally, especially corn and wheat (Hefferon, 2015).
- *The emergence of novel biomaterials based on biotechnology.* Instead of trying to just produce ‘drop in’ bio-based equivalents, completely new bio-based materials with superior engineering characteristics are possible. For example, biotechnology-based spider silk has applications in microphones in hearing aids and cell phones, aircraft structural applications, even in high-value cosmetics (Bell et al., 2021).

- *More versatile microbial production.* Traditional fermentations based on sugars or gases are moving from solely ethanol (as a fuel) to a wider range of chemical building blocks and higher value-added products (e.g., Liew et al., 2022). Gas fermentation is the perfect example for this report as using CO_2 rich industrial waste gases, including those originating from bioresources, relieves pressure on crops and thus land.

Engineering biology, the missing link in biomanufacturing

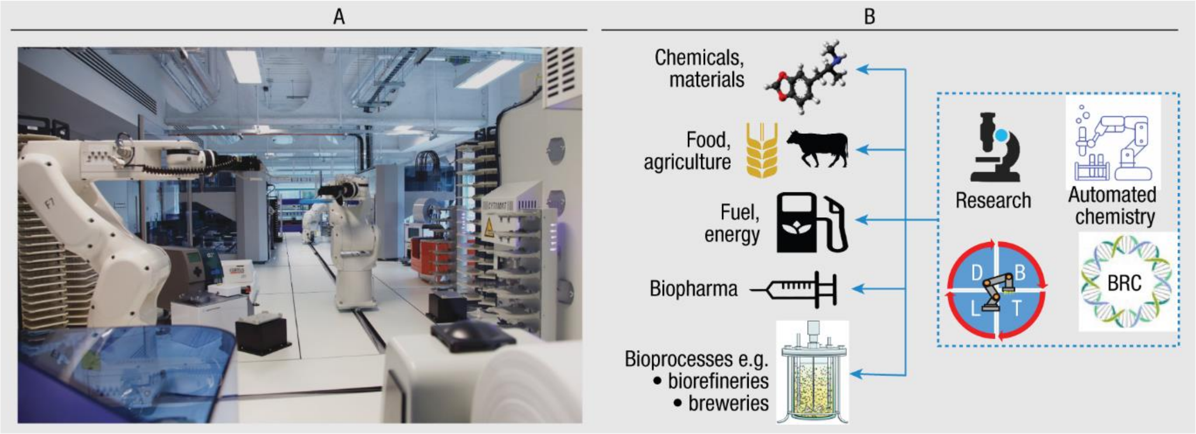
Synthetic biology may be described as the application of science, technology and engineering to facilitate and accelerate the design, manufacture of genes leading to modification of genetic materials in living organisms. It aims to bring an engineering approach to biotechnology by design and engineering of biologically-based parts, novel devices and systems, as well as redesigning existing, natural biological systems. It might be regarded as a technical evolution of metabolic engineering, a technology from the 1990s, which can be described as the use of genetic engineering to modify the metabolism of an organism. It is fairly recently, however, that engineering/synthetic biology has been explicitly linked to climate change e.g., DeLisi (2019) and sustainable development (French, 2019).

Complexity of life forms and their cellular machinery has forced life scientists into a reductionist method of experimentation by examining one factor at a time (OFAT). By contrast in modern manufacturing R&D, design of experiments (DOE) is the systematic method of investigating the relationship between multiple factors and their impact on the process simultaneously[1]. This is very difficult, if at all possible, to do manually in biology. However, the biofoundry concept is allowing this method in bioengineering.

Biofoundries are highly automated facilities that comprise the extensive and coordinated use of laboratory robots (Figure 4.1a) that are programmed to perform specific tasks according to a workflow (Kitney et al., 2019). A hallmark of modern manufacturing is the separation of design from manufacturing. Here, the biofoundry is the design hub, and it can be geographically separated from a biomanufacturing plant by any distance as the design can be transferred digitally. The combination of biodesign tools (BioCAD), including handling of "big data" and multivariate analysis, and biofoundries is rapidly producing a new type of biology - digital biology - that could revolutionise bio-based production by being the important design link to a number of different types of bioproduction and sectors (Figure 4.1b).

Figure 4.1. The biofoundry as the missing link in biomanufacturing

a) The Edinburgh Genome Foundry (b) The interaction of a biofoundry with other infrastructure and sectors



Note: BRC – Biological Resource Centre; DBTL – the Design-Build-Test-Learn cycle.
Source: Figure 8(a) – Courtesy of the Edinburgh Genome Foundry, University of Edinburgh

Technologies for smart and precision agriculture

Agriculture is a sector ripe for technological change that could improve its sustainability. A few examples are given here, with an emphasis on technologies that reduce the demand for critical resources such as land, water and fertilizers. Several of these technologies have been scrutinised for their ability to reduce emissions and complement conservation agriculture (Northrup et al., 2021).

- *Plant-based alternatives to meat and dairy.* These may have the greatest sustainability impacts in food and agriculture. A recent report[2] suggested that improving and scaling up the production of meat and dairy alternatives results in three times greater GHG reductions compared with investment in green cement technology, seven times more than green buildings and eleven times more than zero-emission cars.
- *Vertical farming.* Growing crops under controlled indoor conditions saves water, labour and fertilizer, nullifies runoff, and can drastically shorten the cold chain[3], all the way down to local production in vertical city farms. Vertical farming is currently expanding rapidly, with many investors, start-ups and established greenhouse industry companies entering the space to satisfy the consumer demand for fresh and local food (Van Gerrewey et al., 2022). As with many of these potentially disruptive technologies, there are concerns over the requirement for energy, which accounts in large part for higher costs for these crops, partly responsible for several unsuccessful initiatives (Beh and Dent, 2022).
- *Smart tractors and machinery.* Ninety percent of all energy invested in cultivation is to repair damage to crops and soil caused by tractors[4]. GPS-guided tractors ensure that all traffic follows the same routes, maximising fuel economy and minimising crop damage. But the range of functions is much larger than simply driving. For example, path-generating algorithms can calculate, among others, the size of implements, coverage area patterns, and the implement turn radius (Tripathi et al., 2022).
- *Precision farming.* Robotics and the use of advanced sensor technology are being introduced to optimise resource efficiency. In precision farming the field is divided into a virtual grid where water and fertilizers can be administrated according to varying needs. Precise administration of pesticides allows for reduced environmental burden.
- *Tackling food waste and food distribution challenges.* Using food waste as a raw ingredient demonstrates cascading use and circularity. Instead of throwing away 44% of all bread baked it can be used again by, for example, fermenting it to beer, a technology already in existence through companies such as Toast Ale[5]. The CO_2 resulting from the fermentation is food-grade and is easily collected for use in carbonated drinks.
- *Enzymatic upgrading of bio-residuals.* Enzymes obtained from microbes are commonly known as the key factor in modern detergents. However, enzymes are also important in improved utilisation of biomaterials and food. In Norway, Borregaard[6] is developing enzymes to extract fermentable sugars from solid wood, while several companies are enzymatically converting off-cuts and residuals from the marine industry[7] or poultry[8] into high end products in food and feed.
- *The use of insect bioreactors is an example of a new type of bioproduction.* Cultivating the larvae of various insect species can very efficiently convert carbohydrate-rich residuals into protein and fat, illustrating upcycling of biowaste from e.g., the food industry.
- *Anaerobic digestion.* When opportunities for functional utilisation have been exhausted, anaerobic bacterial culture can process biowaste into methane for heat and electricity, even at individual farm scale (IEA Bioenergy, 2015; see Recycling of wet organic material.

The enigma of meat

As the global middle class increases in size, the demand for meat in the diet increases. To date, livestock occupies almost 80% of global agricultural land, yet produces less than 20% of the calories supply (Poore and Nemecek, 2018). Beef and mutton are the main culprits; the land area they require is up to 100 times larger than for cereals[9]. To keep up with food demand, 13 billion hectares of forest area are lost each year to agricultural uses. This has detrimental effects on regional water availability, soil fertility, biodiversity and climate change.

While biotechnology-based and plant-based meat substitutes are slowly gaining popularity[10] and there is tentative evidence of significant improvements in sustainability compared to conventional meat[11], science advances will need to be accompanied by behavioural changes, and policy can play important roles. In the large (1.2 million people) UNDP climate policy survey published in 2021, one of the two least popular policies overall was plant-based diets (UNDP, 2021).

Breeding for efficiencies in the production of meat and milk, e.g., selection of traits for higher protein content, is increasingly guided by modern methods like genomic markers or CRISPR (e.g., Singh and Ali, 2021). Genomic selection is now a *de facto* standard in leading dairy cattle breeding programmes (Obšteter et al., 2021). The same development is seen in poultry, where genomic selection is used to improve feed conversion ratio and leg strength in chicken. Aviagen (Scotland) became the first company in 2012 to include genomic information in its poultry R&D breeding programme.

The emissions from agriculture are not simply CO_2 as, in fact, methane and nitrous oxide related to animal husbandry constitute the dominant direct emissions, both of which are much more potent greenhouse gases than CO_2. This is one factor that complicates the accounting of agricultural emissions. More research is needed to elucidate how emissions of methane and nitrous oxide contribute to temperature change and how it can be mitigated.

One strategy to reduce methane emissions would be genomic selection of cattle with lower methane production in their gut (Lassen and Difford, 2020). Another strategy which is currently explored, is adding chemical compounds to the feed that selectively knocks out the methanogenic bacteria present in the gut flora. One such compound is the commercially available 3-nitrooxypropanol. A naturally occurring alternative would be bromoform, which can be administrated by adding a small amount of certain red seaweeds to the feed (Kinley at al., 2020). This is spurring the search for additives from a wider range of seaweeds (Mihaila et al., 2022). The Australian company Rumin8 has ongoing trials with an additive that consistently demonstrates more than 85% methane reduction, which equates to two tonnes of carbon emissions removed from the air, per cow, per year[12].

Fertilizer and its alternatives

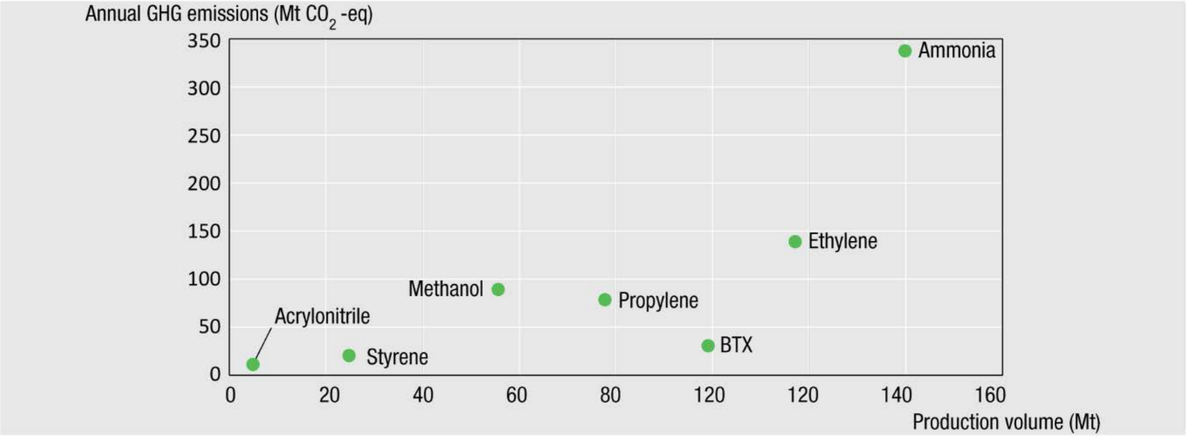
Ammonia (NH_3) is the key nitrogen source in making mineral fertilizer. It contains no carbon, and yet its production process is responsible for about 1.8% of global CO_2 emissions (Figure 4.2), making it the largest CO_2-emitting chemical industry process (IEA, ICCA, DECHEMA, 2013). The process consumes some 1.8% of global energy output each year (Royal Society Policy Briefing, 2020) and around 3-5% of global natural gas (Licht et al., 2014). Fortunately, technological alternatives exist, and major producers of fertilizers are currently exploring production of ammonia where natural gas is replaced with hydrogen produced by electrolysis of water using renewable power.

Meanwhile, Australian researchers have discovered an electrochemical method for production of ammonia from air that relies on a phosphonium cation working as catalyst at ambient temperature and pressure (Jasi, 2022). In contrast to the conventional Haber-Bosch process, this can be miniaturised to container-sized production units generating 1 tonne per day. Such units could be located and used on farms, thus allowing farmers to make fertilizer on demand, an approach consistent with a small-scale distributed manufacturing paradigm.

It should also be noted, however, that there are large environmental problems created by the overuse of mineral fertilizers[13], especially the eutrophication of water courses (Brownlie et al., 2022). Within the IPCC accounting framework, emissions from the manufacture of fertilizer manufacture come under ‘energy’ and effects related to its use, e.g., eutrophication, are not considered in this framework.

Nitrogen fixation for cereal crops would lower the need for mineral fertilizers, or in the best case nullify their requirement. There are two basic technologies. The first is to use nitrogen-fixing engineered bacteria to colonise roots of cereal crops – here there is one commercialised strain that has completed trials and safety procedures (Wen et al., 2021). The second, which is still developing, aims to create novel crops that fix their own nitrogen from the atmosphere (e.g., Rosenblueth et al., 2018).

Figure 4.2. The top GHG emissions producing chemicals



Note: Ammonia, containing no carbon itself, is far above the other highest organic chemicals in emissions. Of all chemicals, its production also has the highest energy demand. The figures are for 2010.
Source: Reproduced from Royal Society Policy Briefing (2020).

Soil, the forgotten resource

Long overlooked by policy makers, soil is the ultimate resource in the bioeconomy: more than 95% of all food is derived from cropland soil and its microbes (Gore, 2013). By 2050, the world will need to produce 50-70% more food, increasingly under drought conditions (Cook et al., 2015), increased fire frequency[14], and on degraded soils (Karlen and Rice, 2015). Meanwhile permafrost thaw could have disastrous consequences by releasing vast quantities of CO_2 and methane to the atmosphere (Schuur et al., 2015).

As important as it is, the ecosystem services provided by soils are grossly undervalued (Baveye et al., 2016). Soil accounts for some 20% of natural removal of human CO_2 emissions (European Commission, 2007), but it is very easily damaged, and very slow to renew. It is estimated that in the past two centuries, soil organic carbon has decreased by 8% globally. Some 20% of the surface of the European Union is subject to soil erosion at a rate of 10 tonnes per hectare per year, leading to a loss of productive land of 1 000 km^2 every year. It is hardly surprising, then, that the FAO regards soil as a finite, non-renewable resource[15]. It is currently being depleted at a faster rate than it is being formed (Handelsman, 2021).

Soil microbiomes

The true value of soil becomes obvious when seen as a biological resource, rather than a simple geochemical entity. Soil microorganisms fix nitrogen, enabling fertilisation. As soil microorganisms are largely responsible for cycling of soil organic carbon (SOC) and other nutrients, their irreplaceable and essential role in climate feedback is now recognised (Jansson and Hofmockel, 2020). If soil has been forgotten as the ultimate resource, it is because the role of soil microbiota in forming and sustaining soils has historically been overlooked (Coban et al., 2022). A greater association between soil microbiomes and the UN SDGs (D'Hondt et al., 2021) would bring greater political attention to soils.

Technologies such as environmental genomics and metabolomics are now untangling the multiple roles that soil plays by detailed examination of the complex web of life that soil hosts – now known as the soil microbiome, comprising bacteria, archaea, viruses, fungi and protozoa. However, there is still a lack of information with respect to the major drivers that trigger microbial community composition and function on all scales (Nannipieri et al., 2019). To this end, the Earth Microbiome project[16] has provided a number of important but voluntary standards for the analysis of soil microbiomes. These facilitate the comparison of data from single projects with studies by other researchers in a meta-analysis.

Carbon farming

Carbon farming constitutes agricultural techniques aiming to reduce GHG emissions by increasing the content of carbon in soil, reaching beyond but also including traditional recycling of biomaterials through manure and leaving straw and crop residuals on the field. While these are management practises rather than technologies (see biochar discussed below), they improve soil health and sequester carbon in combination with important co-benefits, including increased soil water-holding capacity, bioavailability of nutrients, biodiversity, and resilience (Zomer et al., 2017).

The EU Farm-to-Fork strategy[17] intends to reward farmers and foresters implementing carbon farming practices. However, an obstacle to making a reward system is the realistic quantification of the impacts of these practices, a dilemma recognised in the United States SMARTFARM case study (see Recycled and atmospheric carbon). The conservation practices include[18]:

- afforestation and reforestation that respect ecological principles favourable to biodiversity and enhanced sustainable forest management
- 'agroforestry' and other forms of mixed farming combining woody vegetation (trees or shrubs) with crop and/or animal production systems on the same land
- use of crops and conservation tillage that protect soils, reducing soil loss by erosion and enhancing soil organic carbon on degraded arable land
- targeted conversion of cropland to fallow or of set-aside areas to permanent grassland
- restoration of peatlands and wetlands that reduces oxidation of the existing carbon stock and increases the potential for carbon sequestration.

Biochar and CCS

The International Biochar Initiative[19] defines biochar as "solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment". As for carbon farming discussed above, several relevant benefits are promoted for biochar, among them improvements to soil biodiversity and soil fertility. The carbon in biochar is purported to be stable for perhaps thousands of years, raising the concept of pyrogenic carbon capture and storage (PyCCS) (Werner et al., 2018). Schmidt et al. (2019) demonstrated that PyCCS can achieve carbon sequestration efficiencies of greater than 70%, a level considered to be an important threshold to allow PyCCS to become a relevant negative emission technology.

Compostable plastics and soil amendments

Compostability of plastics becomes essential for all applications in which the materials used are highly likely to be polluted by food residues, such as organic waste bags, food packaging, and coffee capsules. When contaminated with food waste, recycling of plastics is not feasible (Schyns and Shaver, 2020), neither with methods designed for plastics, nor as biowaste; thus if these plastics are not biodegradable the probability is high that such waste materials end up in landfills (OECD, 2022).

Two of the case studies for this report, one from Germany (see chapter 5) and one from Italy (see chapter 5) describe the development of a biodegradable and compostable plastic value chain (products such as bags, packaging, or cutlery) together with an efficient system for biowaste collection and recycling. The objective is to make the mixed waste suitable for organic recycling and for the creation of high-quality compost.

Recycled and atmospheric carbon

Recycling of wet organic material

Wet organic wastes such as sewage sludge and agricultural slurries require to be dried before their use in thermochemical processes. That drying process is very energy intensive. The anaerobic digestion of these wet wastes obviates the need for drying, and results in a useful fuel (biogas) which can also be used as a feedstock.

Anaerobic digestion of sewage sludge to produce biogas (a mixture comprising mainly methane and CO_2), has been used for over a century in the biological treatment of wastewater. It stabilises sewage sludge by removing pathogens and at the same time captures a substantial part of the energy in the organic material. The biogas can subsequently be converted to electricity, which can be sufficient to power an entire wastewater treatment plant (Schwarzenbeck et al., 2008), adding to the environmental and economic sustainability of such plants, while decreasing grid dependence.

Anaerobic digestion is highly scalable. It has been perfected down to individual farm level (Figure 4.3), where a variety of waste materials can be converted to biogas (e.g., sludge, grass, solid manure, chicken manure and straw). Moreover, the effluents after anaerobic digestion are better balanced to meet crop needs than raw manure slurries. This reduces the need for supplementary chemical nitrogen and phosphorus fertilizers (Massé et al., 2011), while reducing GHG emissions (Siegmeier et al., 2015).

Figure 4.3. Farm-scale anaerobic digester, Jelsum, Netherlands

Note: The plant is capable of ‘gas to grid injection’, the gas is produced from 7 000 tonnes of manure and 7 000 tonnes of waste products. The plant produces the equivalent of the natural gas for 750 households. The project was realised with a Top Sector Energy subsidy from the Netherlands Ministry of Economic Affairs.
Source: Courtesy of HoSt, www.host.nl/en.

There are many scales and classifications of anaerobic digestion plants, reviewed comprehensively by O'Connor et al. (2021). They posit that small-scale anaerobic digesters (SSADs) offer potential for expansion of the technology in Europe due to the ability to operate economically in small to medium-sized farms with lesser available biomass quantities. National biogas subsidy schemes can strongly support the uptake of SSADs.

Of the European Union countries, Germany in particular has oriented itself towards small-scale biogas plants. German SSAD plant installations increased after the German government introduced an amendment to the Renewable Energy Source Act (*Erneuerbare-Energien-Gesetz*)[20]. This amendment provided a special allowance for biogas plants with an installed electrical capacity up to 75 kW, greatly improving the economics of operating such a plant. In a similar policy approach, the Flanders region of Belgium has seen rapid uptake of SSAD plants in recent years, many of the installations having been supported through the Flemish Climate Fund[21]. The US Federal Energy Regulatory Commission Order 2222 (FERC-2222[22]) incentivises biogas production on United States dairy farms through electricity policy changes (Erickson et al., 2023).

The US EPA offers an Anaerobic Digestion Screening Tool[23] to stakeholders such as farmers to assess the feasibility of the technology on a case-by-case basis. Such guidance is important as scale of operation can determine the cost of electricity generation. This is especially true when anaerobic digestion is linked in policy via feed-in tariffs (FITs) (UK Department of Energy and Climate Change, 2016). A FIT is a national policy mechanism that provides payments and long-term contracts to renewable electricity producers, proportional to the amount of power generated.

Treatment and recycling of dry solid waste

The organic fraction of municipal solid waste (MSW) should ideally be biodegradable and compostable, and there are technologies available for both domestic and industrial composting. Indeed, industrial composting has become a widespread organic MSW treatment procedure (Siles-Castellano et al., 2021). More challenging as a solid waste is plastic waste as the vast majority of fossil-based plastics are not biodegradable and can remain in the environment for decades or longer. International policy interventions to reduce plastic waste since 2005 lack robust monitoring and enforcement measures and are failing to contain the plastics in the oceans dilemma.

Mechanical recycling of polymers

Mechanical recycling is already well established, but it is hardly adequate, as the many reports on plastic garbage in the oceans testify (e.g., IUCN, 2021). Eriksen et al. (2023) estimate there are some 170 trillion plastic fragments in the oceans. In the EU recycling hierarchy mechanical recycling is considered second-best to reuse. Here, plastic products would be sorted and melted and/or remoulded into new products. This is hampered, however, by several obstacles related to the product design. Many products are composites containing different materials and products as well as pigments and other additives which are hard to remove.

More advanced technologies for automated sorting and pre-processing combined with regulations incentivising plastic products designed for recycling may improve the opportunity for cascading use. Meanwhile, plastics are typically downcycled to less advanced products like flowerpots and construction materials. While not optimal, its use in bricks, blocks and tiles would mitigate the negative effects of mining (Lamba et al., 2021).

Chemical recycling of polymers and other dry waste

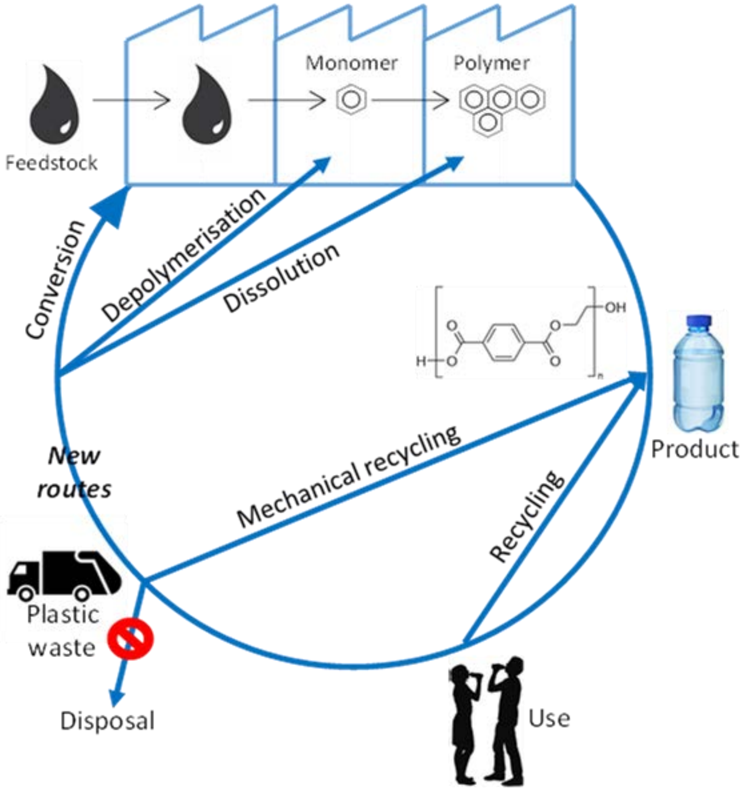
Chemical recycling offers different opportunities by turning plastics or dry mixed waste into a depolymerised secondary raw material (Modesti et al., 2018), thereby closing the carbon loop and creating circularity (cradle-to-cradle) (Figure 4.4). There are at least three mature and industrialised chemical recycling technologies and there are several others at lower stages of development (Solis and Silveira, 2020). They all operate at elevated temperatures, but the intermediate products and thus the following downstream conversion methods and applications will vary.

Pyrolysis, which typically take place at 400-600°C in the absence of oxygen, converts the waste into a gas effluent, an oil fraction and a solid carbon fraction (biochar), which can all be further processed or utilised. The ratio between the oil and the biochar fractions depends on the temperature gradient, as fast pyrolysis typically maximises the oil content. Gasification takes place at higher temperatures, usually close to or above 1 000°C, in the presence of controlled amounts of oxygen. Here, some of the waste feedstock is incinerated to maintain the high temperature (creating some CO_2), while most is converted to synthesis gas, a mixture of CO, CO_2 and hydrogen, where the ratio depends on the composition of the feedstock.

These methods can be adapted to many types of feedstocks, not only plastics, but a large variety of industrial and municipal solid wastes, the dry organic residual from anaerobic digestion or low grade bioresources. Synthesis gas is a particularly interesting and versatile intermediate, as it can be combined with mixtures of CO_2 and hydrogen utilised in CCU or DAC, as will be described below.

To date, there are too few operations at full scale (Figure 4.5) to determine which of these technologies has the greatest economic or environmental advantage. Indeed, this may not be clear-cut in all circumstances as local conditions may dictate a specific technology e.g., volumes of feedstock available, consistency of quality and supply, local policy for recycling, and gate fees[24]. LCA is the tool of choice at present for assessing the feasibility of the technology, but as in other instances, this may only be a useful start-point.

Figure 4.4. Chemical recycling increases the circularity of plastics



Note: While mechanical recycling is decades old, chemical recycling technology is relatively new.
Source: Adapted from https://cefic.org/a-solution-provider-for-sustainability/chemical-recycling-making-plastics-circular.

This should point policy makers in familiar directions e.g., public research funding, R&D subsidy or other forms of public-private partnership as de-risking instruments. In Europe, for example, there are 225 million tonnes of municipal waste generated per year, or about half a tonne per person[25] of which only about 30% is recycled, 27% is incinerated and 24% still ends up in landfill. This includes 25.8 million tonnes of plastics waste where only about the same fraction (30%) is being collected for mechanical recycling. (European Commission, 2018). There is clearly a need to increase the market and profitability in recycling, whether by mechanical or chemical processes.

Figure 4.5. Shell is building a chemical recycling plant in Singapore

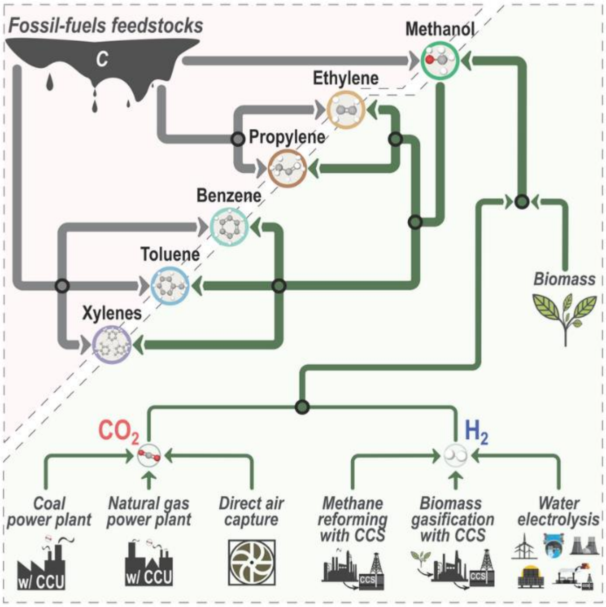
Note: Slated to start production in 2023, the unit at Shell's manufacturing site on Pulau Bukom will be the largest in Asia and Shell's first globally, with a capacity of 50 000 tonnes per year, equivalent to the weight of about 7.8 billion plastic bags.
Source: Courtesy of Photographic Services, Shell International Limited.

Technologies for utilisation of industry flue gases (CCU)

C1 pathways, especially methanol

As shown in Figure 4.6, a large proportion of organic (carbon-containing) chemicals are made from a small number of platform molecules, methanol, three aromatics (xylene, toluene and benzene) and the two olefines (ethylene and propylene). The latter can in principle be synthesised from the C1-molecule methanol, underscoring its importance as a key intermediate. Add butadiene to this list, and these seven molecules constitute the platform that serves more than 90% of organic chemical production, including tens of thousands of products (Tickner et al., 2021). Furthermore, ethylene and propylene are used to make polyethylene and polypropylene, which together make up more than 50% of all non-fibre plastics (Geyer et al., 2017), and are in everyday use in many bulk applications around the world.

Figure 4.6. Summary of routes to the major platform chemicals



Note: Methanol can be processed to five other major platforms.
Source: Galán-Martín et al., 2021

The production of methanol, typically from natural gas, has nearly doubled in the last decade, and demand for methanol is going through a period of rapid expansion (SOTACARBO, 2020). Replacing fossil methanol with a CO_2-based route (CCU) could lead to a closed-carbon chemical sector, perhaps even orchestrating a negative emissions balance, sequestering CO_2 in long-lived plastics or construction materials (Hepburn et al., 2019).

The main objection to using CO_2 as a feedstock, however, is that its thermodynamic stability makes a reaction with hydrogen to methanol very energy demanding, in a typical case provided by hydrogen in the form of energy rich hydrogen gas (H_2). However, the CO_2 and hydrogen feedstocks can both be generated from either fossil or renewable resources. This flexibility of feedstock together with its general utility, makes CO_2-based methanol production an especially interesting case in carbon management.

Methanol can also be produced from biomass and has been made from domestic waste at commercial scale my Enerkem of Canada[26]. It will typically go via gasification of the bioresource to create synthesis gas (CO, CO_2 and H_2), followed by essentially the same downstream processes as used in the CCU route. To date, the green routes to this vital platform chemical remain uncompetitive but could be competitive by 2030 given some assumptions (Schorn et al., 2021). What is clear, however, is that the main barrier to renewable methanol uptake is not a lack of technology, but its higher cost compared to fossil fuel-based alternatives, and the potentially limited availability of renewable energy.

Replacing fossil methanol with a renewable alternative could offer a significant reduction in CO_2 emissions in the chemical sector. Moreover, being a currently used platform chemical would allow for a simple drop in substitution without the need for major changes in process design and retrofitting of manufacturing infrastructure.

Outside its central importance in the chemicals industry, renewable methanol is being suggested as a solution in another hard-to-abate sector – shipping (Andersson and Salazar, 2015). While light vehicles are increasingly electric, replacement of fossil fuels in heavy transport such as aviation and shipping is a bigger challenge. Mærsk, the shipping giant, recently increased its investments in renewable methanol-fuelled container vessels[27].

C2 – C4 pathways

A direct non-fossil production of longer carbon molecules, such as the alcohols; ethanol, propanol, and butanol (C2-C4), is typically done by microbial fermentation. However, the cost, the land, nutrients and energy resources required to produce sugar substrates for the microbes makes this route to simple commodity platform chemicals less attractive (Scown and Keasling, 2022). In order to avoid conflicts with food production, so-called second-generation sugars from e.g., cellulose could be used, but this technology is still immature and, in most cases, prohibitively expensive.

After several decades of work on (ligno)cellulosic waste as a feedstock, the technology is still unproven. New breakthroughs in consolidated bioprocessing (CBP) research have been qualified by the potential needing to be "improved by metabolic and process engineering for higher yields of ethanol production and plant biomass utilization" (Maleki et al., 2021).

Another, perhaps more near-term route to C2-C4 chemicals is gas fermentation. Here, microbes use carbon gases such as CO_2 or CO as carbon source and H_2 gas as hydrogen and energy source, thus providing a biotechnological approach to utilising the same gases as described above for chemical methanol production. Again, the main benefit is flexibility in the source of such gases and if industry flue gases are being used, there is virtually no requirement for land.

The microbial fermentation of waste industrial gases to useful products such as ethanol (Liew et al., 2016), acetone (Liew et al., 2022) and animal feed (Pander et al., 2020) is becoming reality. These processes can still be improved, however, and genetic engineering and synthetic biology are capable of further developing gas fermentation as a highly versatile manufacturing platform with great potential for scaling.

There are various ways that fermenting waste gases to products contributes to sustainability. It is one of the emerging technologies of CCU (Zhu, 2019), effectively a value-adding strategy compared to CCS. A cradle-to-grave LCA for the production of ethanol by gas fermentation estimated a 67% GHG reduction using steelmaking off-gases compared to conventional fossil gasoline (Handler et al., 2016). Off-gas from steel mills is a convenient feedstock because they comprise a high proportion of carbon monoxide (CO), which in contrast to CO_2 contains energy. If renewable hydrogen is added, the carbon efficiency of the fermentation process increases, i.e., the amount of carbon incorporated into the ethanol product.

As already mentioned, gas fermentation can also use synthesis gas produced via gasification (Liakakou et al., 2021) from a range of sources such as agricultural residues, forestry waste, sorted plastics or municipal solid waste, as well as CO_2 from any source, including direct air capture (DAC) supplemented with hydrogen[28]. When the CO_2 (or part of it) originates from biogenic material or from DAC, the products made can in principle be fully renewable.

Fossil feedstocks: electrifying the process

Figure 2.2 suggests that fossil raw materials will still be in use in the chemicals industry for decades to come. That being the case, there is a need to abate emissions within existing oil refineries and chemical production plants until such times as fossil replacement technologies are feasible. Steam cracking[29] is a crucial process in the chemical production chain and is of one of the most energy-intensive processes in the industry, resulting in a large source of its CO_2 emissions. Typically steam cracking is done in furnaces at around 850°C by burning fossil fuels like natural gas. If cracking can be electrified using sustainable solar and wind power instead of fossil-based fuels, CO_2 emissions can be greatly reduced.

The German Federal Ministry for Economic Affairs and Climate Action has granted EUR 14.8 million to support the development of a novel furnace technology with BASF, SABIC and Linde at the BASF Verbund site at Ludwigshafen. By using electricity from renewable sources instead of natural gas, the new technology has the potential to reduce CO_2 emissions by at least 90% compared to technologies commonly used today[30]. This is a world first demonstration plant for large-scale electrically heated steam cracker furnaces.

Microbial single cell protein for food and feed

Protein is an essential component of food and feed. Microbial production of protein, so-called single cell protein (SCP), was a full-scale industry 50 years ago but started to fail during the 1970s oil shocks (Groenewald et al., 2014). Today, pressure on natural resources has revived interest in SCP from various sources, e.g., first and second generation sugars. As for chemicals discussed above, gas substrates such as methane, waste-to-syngas and off-gases (Jones et al., 2020) have all become interesting alternatives to sugar-based fermentation. An interesting theoretical study has suggested that gas fermentation based on energy from sun panels could increase protein yield five-fold per area, compared to sugar fermentation and fifteen-fold compared to conventional cultivation of soya (Leger et al. 2021). New technologies such as CRISPR have greatly increased the potential for optimising SCP production to support a rising demand for protein associated with high land use in agriculture and low conversion efficiency of meat production.

Aquaculture is the fastest-growing food industry in the world and already produces more biomass than either wild seafood or beef (Froehlich et al., 2018). It addresses some key issues of sustainability, but also dilemmas. Fish farming entails significantly lower emissions than ruminant production. Also, aquaculture takes pressure off wild fisheries, vital for the future as over one-third of global wild fisheries have been exploited beyond sustainable limits (FAO, 2020). While the potential for further growth of aquaculture is way above wild fisheries, such expansion will need new sources of quality protein feed with lower environmental impacts than soybean protein (da Silva et al., 2021). Internationally, there are several companies actively pursuing gas fermentation for the production of feed ingredients.

Technologies for capturing and use of atmospheric CO_2 (DAC)

In photosynthesis, plants extract and fix CO_2 from the air by converting it to biomass with the help of sun energy. In so-called industrial direct air capture (DAC), CO_2 is captured and concentrated by industrial processes, either to be utilised (as plants do) or removed from the atmosphere by sequestration (CDR).

Currently, there are two categories of DAC furthest along in development, solid sorbents and liquid solvents (Figure 4.7), while there are other pathways less well developed.

Liquid solvent-based DAC

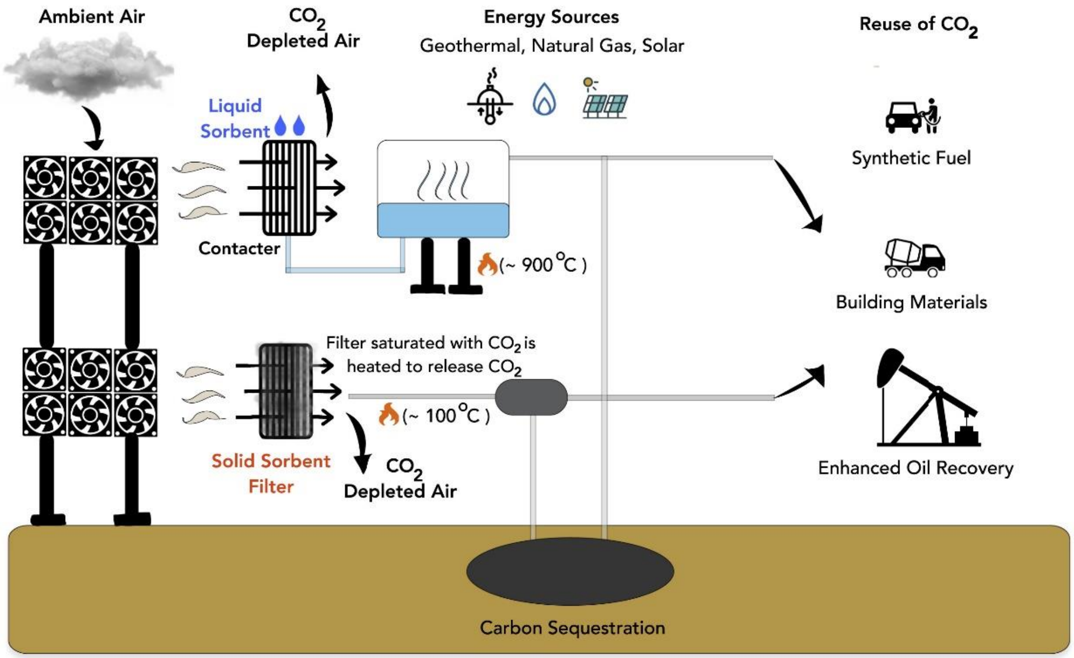
In the solvent-based approach, gaseous CO_2 in air is absorbed into a liquid solvent, resulting in a CO_2-depleted *gaseous* exhaust stream and a CO_2-rich *liquid* exhaust stream. The typical solvent-based approach requires a strong alkaline hydroxide solution to achieve adequate separation of the very dilute CO_2 in air. Subsequent anionic exchange results in precipitated calcium carbonate pellets. To complete the cycle, high temperature is used to recover CO_2 from the precipitated calcium carbonate and recycling the alkaline reagents. The need to funnel large volumes of air past the absorbing solvent, as well as the regeneration process, drives high energy requirement.

In 2015, Carbon Engineering[31], a Canadian company, started operating a pilot plant in Squamish, British Columbia. The pilot captures roughly 1 tonne of atmospheric CO_2 per day. Recently, the investment decision was made to construct the world's first megatonnes DAC facility in Texas in partnership with Occidental 1PointFive and a second plant is undergoing front-end planning and engineering[32]. This progress is stimulated by the extensive support programme of the Federal US Inflation Reduction Act[33]. In both Norway and the United Kingdom, a similar DAC facility is being considered, where the CO_2 is intended partly for sequestration and partly for use in the production of aviation fuel.

Solid sorbent-based DAC

Solid sorbents have the benefit of the CO_2-reactive compound (typically amines) being chemically bound to a solid framework of the air contactor. The desorption and regeneration of the sorbent takes place at a much lower temperature compared to the carbonate-based method described for Carbon Engineering. Moreover, with an operating temperature of 100-120°C, this process may benefit from co-locating with industry offering surplus of heat or the use of geothermal energy exemplified by the Climeworks[34] demonstration plant in Iceland (4 kilotonnes per year). This potential energy and cost benefit is possibly countered by a presumed higher CAPEX upon scaling. Interestingly, also Climeworks is engaged in a project in Norway aiming to use DAC for production of aviation fuel.

Figure 4.7. DAC processes combined with CCS and/or CCU



Note: Both Carbon Engineering and Climeworks have CCU projects to produce synthetic fuels. For example, Norsk e-fuel is developing a hybrid technology with Climeworks to take captured CO2 and make a drop-in aviation fuel.
Source: Diagramme from Ozkan et al. (2022).

Carbon sequestration for compensation and removal

Sequestration in building materials

Solid wood construction

The new European Forest Strategy[35] of 2021 foresee that forestry could "…contribute to achieving the EU's biodiversity objectives as well as greenhouse gas emission reduction target of at least 55% by 2030 and climate neutrality by 2050." There are several ways for forestry to contribute, and one is through increased use of wood and timber in construction to reduce the reliance on concrete. Carbon is sequestered in buildings in this way for many decades or even centuries, and when designed for disassembly and reuse, can be an extremely low-emissions and resilient building material. Skullestad et al. (2016) used LCA to compare timber with concrete and steel as high-rise construction materials with regard to climate change mitigation potential. Timber materials had a significantly lower primary CO_2

footprint, and if 90% of timber production residues and timber material waste were incinerated with heat recovery to replace natural gas, a timber structural system can be emissions negative.

Mass timber is a transformative technology made by affixing or gluing together many pieces of wood veneers, flakes or dimension lumber to form larger, stronger pieces of building materials such as solid wood panels, columns or beams that are often used for load-bearing walls, floors and roof construction. There are several types of engineered mass timber products, which are typically categorised by the types of wood products involved and the way they are bound together. The most commonly used types of engineered mass timber products include cross laminated timber (CLT), i.e., large panels of lumber laid flat and combined with alternating direction of the wood fibres. CTL can then be subdivided into nail laminated timber (NLT) and glue laminated timber (GLT) (Figure 4.8).

Figure 4.8. Brock Commons timber-framed high-rise building, Canada

An 18-storey wood hybrid building, University of British Columbia

Note: See Canada 1: Embedding carbon in the build environment.
Source: Courtesy of Natural Resources Canada https://natural-resources.canada.ca/home

Engineered mass timber products are engineered for high strength ratings like concrete and steel but are significantly lighter in weight. Prefabrication means that on-site building construction is significantly faster. Moreover, they can be designed specifically for fire resistance, are energy efficient as the low thermal conductivity of wood provides natural insulation that reduces heat loss, and they are well suited to earthquake prone regions due to their durability (Zanuttini and Negro, 2021). Given these functional advantages, combined with the climate benefits, mass timber buildings are slowly being accepted as a sustainable alternative to concrete and steel construction materials (Cabral and Blanchet, 2021).

Injecting CO_2 in cement

Portland cement is the most used human-made material (Monteiro et al., 2017). The cement industry has the highest carbon intensity of any industry per unit of revenue and is responsible for approximately 7% of anthropogenic emissions. Unfortunately, concrete is essential also for future construction, and as already discussed, emissions are unavoidable, calling for CCS or other carbon management strategies.

Interestingly, Miller et al (2021) pointed out that cementitious products can absorb and incorporate large amounts of CO_2 from many possible sources, thus combining CCU and CCS. Captured CO_2 can be reacted with activated minerals or industrial wastes to form stable carbonate minerals. Recent evidence suggests that these minerals create valorisation in their own right, but there is also large potential for their use as supplementary cementitious materials (SCM). Cement replacement such as SCM is the most credible application as others do not match the scale of emissions from cement production and offers several advantages over simple CCS (Skocek et al., 2020). When CO_2 is injected into wet concrete, nano-scale calcium carbonate is formed in the concrete as it dries. As well as lowering the carbon footprint, this approach also results in stronger concrete material, which reduces consumption of cement in concrete making. Therefore, the cost of the CO_2-containing concrete is cheaper than conventional concrete, which lowers the need for public market incentives.

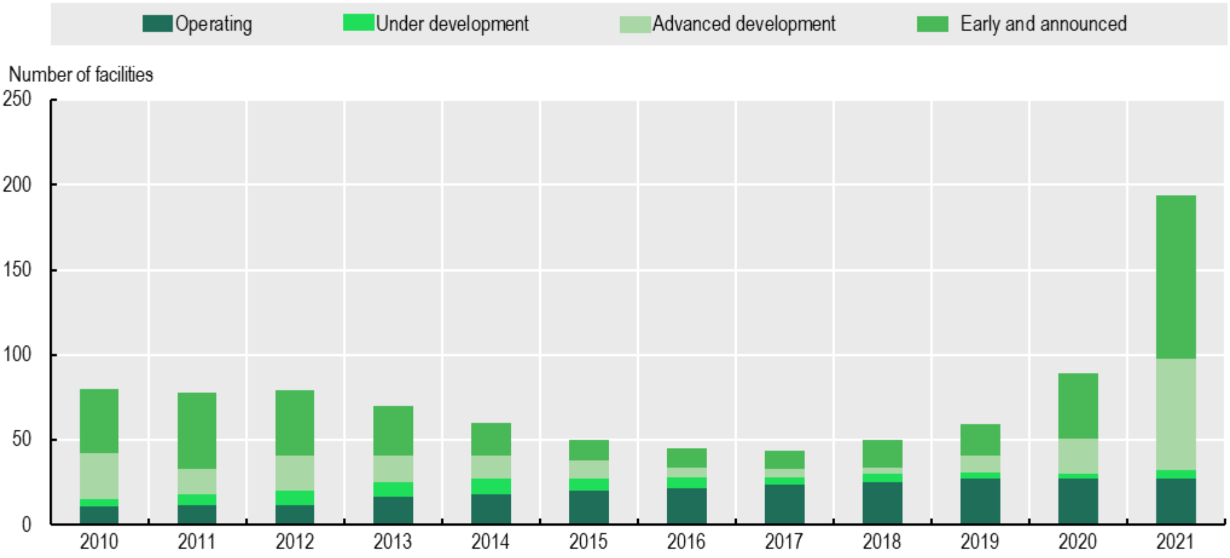
Geological storage

Sequestering CO_2 in deep geological reservoirs is seen as a potential mitigation strategy to reduce anthropogenic CO_2 emissions to the atmosphere, and among the most promising of these reservoirs are depleted offshore oil and gas reservoirs (IPCC, 2005). A geological CCS map of the Norwegian part of the North Sea suggests a total storage potential of 70 gigatonnes in this area alone[36]. As of September 2022, the total global capacity of CCS projects in development was 244 million tonnes per annum of CO_2, an increase of 44% over the previous 12 months[37].

The IEA has argued consistently that there is no alternative to CCS as the solutions for tackling emissions from heavy industry sectors are often extremely difficult or expensive, hence CCS is an important part of carbon management. However, the Institute for Energy Economics and Financial Analysis (IEEFA) (Robertson and Mousavian, 2022) argue that CCS is a 50 years-old technology and even today the number of success stories is outweighed by failures or underperformance. Clearly there is still work to be done.

While CCS certainly still face challenges, the combination of strengthened climate goals and public programmes, an improved investment environment and new business models have set the stage for greater success in coming years. For more than a decade the number of new projects was low and not encouraging, but 2021 saw a revival (Figure 4.9).

Figure 4.9. Global pipeline of commercial CCUS facilities operating and in development, 2010-2021



Source: IEA, Global pipeline of commercial CCUS facilities operating and in development, 2010-2021, IEA, Paris www.iea.org/data-and-statistics/charts/global-pipeline-of-commercial-ccus-facilities-operating-and-in-development-2010-2021

One of the reasons for this improvement has been policy measures and government initiatives. In the United States the expansion of the 45Q tax credit in 2022, providing a credit of USD 85 per tonne of CO_2 from industrial and power facilities that is permanently stored, was a major catalyst for new investment plans. Supported by NOK 18 billion from the government, the Norwegian "Long Ship Project"[38] aims to establish the first complete value chain for carbon capture from industry point sources, transporting the

CO_2 to a centralised hub and storing it permanent below the North Sea. In Australia, AUD 250 million in funding has been announced for CCUS hubs alongside the inclusion of CCUS under the Emissions Reduction Fund[39] (with associated credits valued at around AUD 20 per tonne of CO_2). The US Inflation Reduction Act of 2022 increased the range of measures available for CCS through 45Q (Box 4.1).

Box 4.1. The US Inflation Reduction Act and DAC

The Inflation Reduction Act of 2022 (IRA) included an historic investment of USD 369 billion in climate and energy funding, as well as important enhancements to the Internal Revenue Service section 45Q on carbon capture and storage. The basis was that global CCS capacity needs to scale from today's 40 million tonnes per year to multiple gigatonnes per year by 2050, and this law includes provisions that enhance the financial viability of CCS projects in the United States.

The specific 45Q enhancements contained in the IRA include:

- Extending the start of construction date from January 2026 to January 2033
- Lowering the threshold for captured qualified CO_2
  - Direct Air Capture – 1 000 tonnes
  - Electricity generating facility – 18 750 tonnes (based on certain design criteria)
  - Any other industrial facility – 12 500 metric tonnes
- Increasing the credit amounts
  - Point source capture and storage from industrial and power facilities - USD 85 per tonne
  - Carbon capture and utilisation including enhanced oil recovery - USD 60 per tonne
  - Direct Air Capture
    - Capture and storage of carbon – USD 180 per tonne
    - Capture and utilisation of carbon – USD 130 per tonne

Source: https://daccoalition.org/what-the-inflation-reduction-act-means-for-direct-air-capture/

Capture in sediments (between strata)

One of the anxieties around CCS in engineered underground repositories is the potential for escape if the reservoir is not properly sealed. For offshore sites, the impact of any leakage of stored CO_2 into the marine environment is not well known or understood. Leakage of CO_2 from CCS reservoirs in shallow waters might reduce biodiversity and might also disrupt ecological functions (Lichtschlag et al., 2021).

Injecting CO_2 into deep-sea sediments, however, may provide permanent geological storage with fewer worries (Eccles and Pratson, 2012). At the high pressures and low temperatures common in deep-sea sediments, CO_2 resides in its liquid phase and can be denser than the overlying pore fluid, making the injected CO_2 gravitationally stable (House et al., 2006). This has been carried out safely in Norway for at least 20 years[40].

Mineralisation

The earlier mentioned anxiety around CO_2 leakage from underground and sub-sea reservoirs is negated in the case of mineralisation[41]. This is a natural process that can be reproduced artificially. It results in CO_2 being converted to solid carbonates, which then cannot re-enter the atmosphere. Mineralisation can be carried out at the surface using already mined rocks, or in deep underground formations, both with different costs. In Iceland the Swiss company Climeworks is storing DAC-derived CO_2 as calcite or other carbonate minerals in relatively freshly formed basaltic rocks (Snæbjörnsdóttir and Gislason, 2016).

BECCS and DACCS

Biomass fixes CO_2 from the atmosphere during growth and when this biomass is used for energy purposes, as in combustion, it is released again as concentrated CO_2. If such biogenic CO_2 is captured and stored by geological sequestration or, in the case of biochar formation, applied to land to condition soil, CO_2 is removed from the atmospheric cycle. This process is generally referred to as bioenergy with carbon capture and storage (BECCS) or more generally carbon dioxide removal (CDR), involving negative emissions technologies (National Academies of Sciences, Engineering, and Medicine, 2019). Policy would have to drive BECCS with afforestation, in order to make the case for BECCS being truly carbon-negative stronger.

Presumably, due to the need for sustainable procurement of biomass, BECCS deployment is not always treated and/or rewarded in policy and regulations in the same way as emissions sequestered from fossil fuels. For example, at the time of writing, biogenic emissions under Canada's Output-Based Pricing System (OPBS)[42] are exempted from the price on carbon given their carbon neutrality. However, sequestration of these emissions do not generate credits under Canada's OBPS like sequestration of emissions from fossil fuels. While it does not prohibit BECCS deployment, it does not incentivise the deployment of net-negative technology that could be used to rapidly reduce emissions in heavy emitting sectors. Therefore, treatment of biogenic emissions and net-negative technology will be an important policy and regulatory conversation for carbon management.

Another route to carbon dioxide removal is industrial capturing and concentrating CO_2 from ambient air (DAC), as described in Technologies for capturing and use of atmospheric CO_2 (DAC). From the scenarios in the fifth assessment report of the IPCC (IPCC, 2014) with a chance of more than 66% to reach the 2°C target, the majority considers directly removing CO_2 from ambient air. However, to have any impact, DAC technologies have to be scaled up rapidly. At the time of writing there are 19 plants in operation worldwide, but capturing only about 10 000 tonnes per year, a minute fraction of what is required on the trajectory to net-zero carbon by 2050.

Further technological enablers in carbon-based value chains

Nanotechnology: potential across many CCU areas

Nanotechnology is expected to have a significant impact in all existing industrial sectors, and to harbour the ability to enable the creation of entirely new sectors (OECD, 2017). The main hurdle to achieving commercial-scale production has been insufficient understanding of physical and chemical processes at the nanometre scale, and the inability to control production parameters at that scale, although progress is being made. In this regard, publicly funded cleanroom and nanofabrication infrastructure allows public sector scientists and companies to work together (Figure 4.10).

Figure 4.10. The cleanroom at the LIT Open Innovation Centre (OIC), Austria

Funded by the Austrian Federal Ministry of Education, Science & Research (BMBWF), the Johannes Keppler University (JKU) and the state of Upper Austria.

Note: The LIT OIC is a collaborative platform where cross-disciplinary academic/scientists and faculty members work alongside company representatives to not only share their expertise and resources, but also create successful synergies. The centre follows a visionary and holistic technological approach with a focus on Responsible Technology. It offers a cleanroom[43] and nanofabrication infrastructure which is open for CCUS related projects and activities. The Johannes Keppler University is collaborating in two CCU projects:

1. CO2EXIDE (H2020): CO_2-based electrosynthesis of ethylene oxide. Objective: The establishment of an electrochemical process for the production of ethylene from CO_2, water and renewable energy[44].
2. ENZYMBIOKAT – Enzymatic bioelectrocatalysis for CO_2 reduction. Objective: Conversion of renewable energy (solar and wind) into chemical fuels[45].

Source: Photograph courtesy LIT Open Innovation Centre, Austria.

Nanomaterials can be designed to improve the energy efficiency and selectivity of CO_2 conversion to fuels and other products, thereby having potential roles in CCU[46]. One reason is that, as catalysis is very common in industries, nanocatalysis may be used to improve production and energy efficiencies within existing industrial infrastructure. Another is that new nanocatalysts may be deployed that directly convert emissions into useful products and fuels (Mishra et al., 2020).

Dry reforming of methane with CO_2 creates a mixture of hydrogen and carbon monoxide (CO) - synthesis gas, or syngas - which can be converted into liquid fuels. It has been a problematic reaction, but a process has been developed using highly stable nanoparticles to overcome operational instabilities (Song et al., 2020). The nanocatalyst is made from inexpensive and abundant materials. Its novelty is that it initiates and speeds up the rate of reaction that converts CO_2 and methane into hydrogen gas.

In another example, In_2O_3 nanoparticles have been demonstrated to selectively catalyse CO_2 hydrogenation to green methanol with high stability (Frei et al., 2019). For the reasons detailed in previous sections, methanol is a versatile target for CCU for its roles in chemistry and also as a fuel. Although this and other metal nanocatalysts show promise in the hydrogenation of CO_2 to methanol, many barriers still need to be overcome to reach commercialisation (Zheng et al, 2020).

Nanotechnologies have other applications in climate mitigation more generally. Lightweight nanocomposites for materials in transportation save on fuel consumption or improve other properties that lead to higher process efficiency (Graziano et al., 2020). Nano-based lubricants in engines can significantly decrease fuel consumption by reducing friction (Mousavi et al., 2020). Nanocoatings on, say, the surface of aircraft reduce drag and thus reduce fuel consumption[47]. Cerium oxide nanoparticles as fuel additives aid more complete combustion in engines (Mei et al., 2016). Nanomaterials can help make lighter, stiffer wind turbines (Mishnaevsky Jr et al., 2017). Other applications include photovoltaic technology for solar cells (El Chaar et al., 2011); hydrogen and fuel cells and the hydrogen economy (Sahaym and Norton, 2008); batteries and super-capacitors for energy storage (Gogotsi and Penner, 2018); improved insulation for houses and offices (de Guinoa et al., 2017).

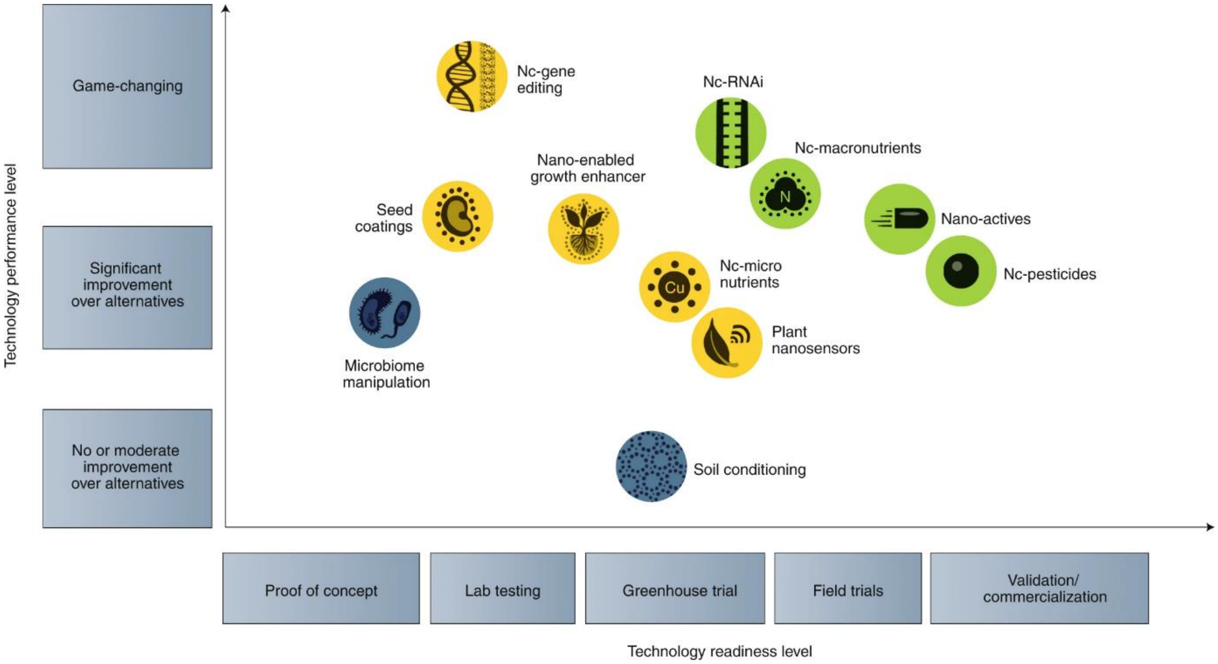
At the cutting edge of nanotechnology/hybrid technologies are nanocell hybrids, which are formed by hybridising abiotic materials with living cells to perform a range of sustainability-driven functions: clean energy, green chemical catalysis, environmental remediation. Nanocell hybrids is a new field that is truly cross-cutting and convergent, encompassing as it does nanotechnology, physics, chemistry, biology, materials science and engineering (Geng et al., 2022).

Nanotechnology in plant agriculture – opportunities and challenges

As an illustration of the general-purpose nature of nanotechnology, Figure 4.11 shows some of the potential applications of nanotechnology in plant agriculture. The authors (Hofmann et al., 2020) assessed that smart delivery of pesticides or nutrients (fertilizers) packaged into nano-carriers are the most mature applications and with the largest potential impact. There are data gaps to be filled, however, to accurately weigh up their risks and benefits. Critical assessment of the market potential and scalability is needed for successful deployment.

Regulation and safety remain critical policy issues and barriers. The engagement of international organisations is required to encourage standardised approaches to nanomaterial regulation. Another barrier is that, unlike other industries for instance pharmaceuticals and automotive, the agricultural industry lacks a unified voice and the resources to develop academic–industry collaborations. And, of course, public acceptance will require engagement of all stakeholders - government regulators, researchers, manufacturers, farmers, consumers and retailers.

Figure 4.11. Nanotechnologies and nanomaterials have applications at many stages in agriculture



Notes: TRL was determined based on the data available on the maturity of the technology, including the scale at which the materials or approach have been applied, the number of studies that provide evidence of efficacy, and the number of commercially available products. TPL was determined based on expert judgment of the potential magnitude of the impacts that each technology may provide to improve agricultural sustainability. Colours indicate the level of opportunity as high (green), medium (yellow) or low (blue). Nc = nano-carrier.
Source: Hofmann et al. (2020)

Automated synthetic chemistry

Compared to the other general-purpose technologies described (synthetic biology/engineering biology, nanotechnology), this is perhaps the least developed. But when perfected, it could herald a "new wave of innovation in biology and materials sciences by greatly facilitating access to known and novel molecules" (Collins et al., 2020). Automated chemical synthesis gets likened to the revolution in genome sequencing, but the main reason that it lags behind biology is that the number of combinations of atoms, particularly in organic molecules, is astronomical, and the technology to build any arbitrary chemical molecule does not yet exist (Sanderson, 2019). While the achievements of modern chemistry are most impressive, current approaches to design and synthesis are still slow and inefficient, with poor reproducibility and scalability, and they make limited use of prior knowledge.

A highly relevant example is a project in automated synthesis to find catalysts that can help to extract hydrogen from water more efficiently. It has taken 20 years of photocatalysis to reach a 1% efficiency in using light to produce hydrogen from water. The goal of the automated synthesis project is to find a material with 5% efficiency, which may mean screening several hundreds of thousands of different molecules. A robotic platform has been built at the University of Liverpool, UK to tackle the task. The ideal automated synthesis platform would be able to plan its own synthetic routes and to execute them, incorporating scale-up to production goals (Coley et al., 2019).

Hydrogen as enabler in carbon-based value chains

In biology, the carbon cycle is the redox process in which carbon oscillates between being bound primarily to oxygen and primarily to hydrogen. Generally, this cycle is driven by sun energy through photosynthesis, whereby atmospheric CO_2 and hydrogen, typically from water, is converted into hydrocarbons. Hence, to reduce the pressure on nature by utilising CO_2 from industry emissions (CCU) or industrially captured atmospheric CO_2 (DAC), hydrogen is a necessary component.

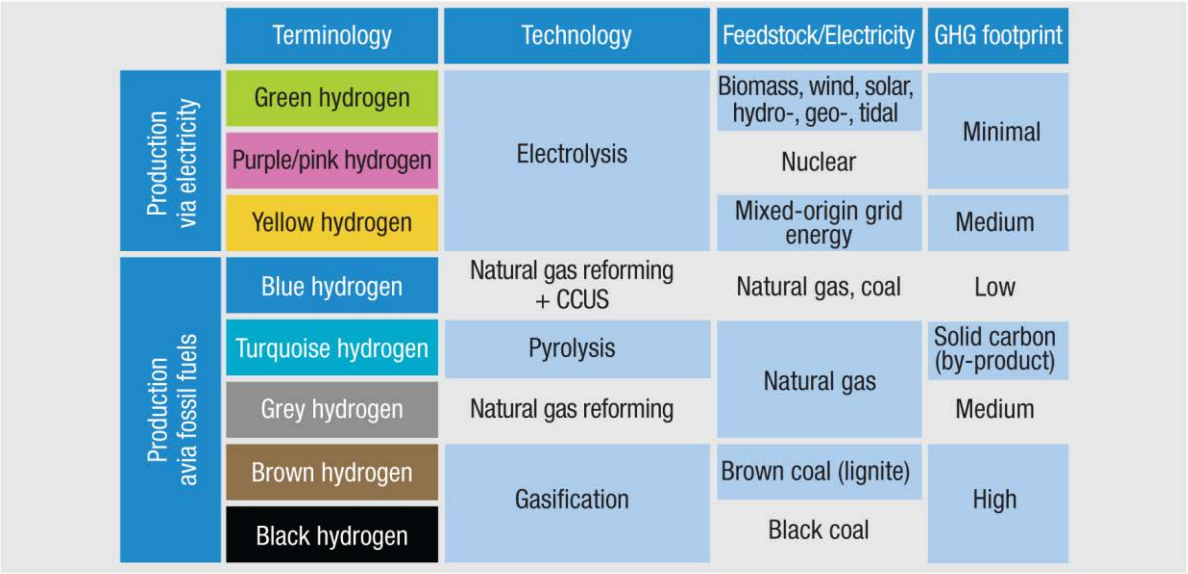
The energy needed to make hydrocarbons is reflected in the fact that the chemical industry is very energy demanding. In a fossil economy, the hydrogen is provided by already existing hydrocarbons such as natural gas or crude oil. To make green alternatives, hydrogen is usually provided as H_2 gas, which is a sufficiently energy rich form of hydrogen to react with CO_2. However, consistent with common practice, the following discussion refers to H_2 simply as hydrogen.

Hence, hydrogen is an essential resource in many carbon-based value chains, not only in CCU and DAC alluded to above, but in a wide spectrum of processes for recycling, upgrading, or converting organic (carbon-based) compounds and materials. This section describes technologies and policies related to hydrogen primarily with reference to manufacturing of carbon products, without downplaying the importance of hydrogen itself as an energy carrier in the energy sector. Hydrogen will also have indirect effects on other value chains, for instance replacing coal as reducing agent in the steel industry or replacing natural gas in the manufacturing of fertilizers.

Production of hydrogen

Figure 4.12 provides an overview of the various production routes to hydrogen, which in industry jargon have been denoted by colours depending on the energy source used. The two most discussed low-emission alternatives are green hydrogen produced from renewable power and blue hydrogen made from natural gas with sequestration of the fossil carbon (CCS). Turquoise hydrogen is a third alternative based on natural gas, where the fossil carbon content is captured on the form of solid carbon (carbon black).

Figure 4.12. The hydrogen economy ‘colours’



	Terminology	Technology	Feedstock/Electricity	GHG footprint
Production via electricity	Green hydrogen	Electrolysis	Biomass, wind, solar, hydro-, geo-, tidal	Minimal
	Purple/pink hydrogen		Nuclear	
	Yellow hydrogen		Mixed-origin grid energy	Medium
Production avia fossil fuels	Blue hydrogen	Natural gas reforming + CCUS	Natural gas, coal	Low
	Turquoise hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey hydrogen	Natural gas reforming		Medium
	Brown hydrogen	Gasification	Brown coal (lignite)	High
	Black hydrogen		Black coal	

Note: United States is moving toward clean hydrogen criteria with well-defined LCA targets versus hydrogen defined by colour.
Source: Adapted from World Energy Council (2021).

Green hydrogen

The generation of green hydrogen is achieved by electrolysis of water powered by renewable energy rather than production from natural gas. Electrolysers consist of an anode and a cathode separated by an electrolyte, much like a fuel cell. Different electrolysers function in different ways, depending on the type of electrolyte material involved and the ionic species it conducts:

- *Polymer electrolyte membrane (PEM).* In this case the electrolyte is a solid speciality plastic material. The special property of this membrane is that it allows passage of protons but not gases such as hydrogen or oxygen, preventing the product gases from mixing.
- *Alkaline electrolysers.* These have been available for many years. Hydroxyl ions (OH^-) pass through the electrolyte from the cathode to the anode with hydrogen being generated at the cathode. Research is investigating the use of solid alkaline exchange membranes (AEM).
- *Solid oxide electrolysers.* These use a solid ceramic material as the electrolyte that selectively conducts negatively charged oxygen ions (O^{2-}) from the cathode to the anode, leaving the produced H_2 at the cathode.

Hydrogen production via electrolysis using renewable (biomass, wind, solar, hydro, geothermal) or nuclear energy options result in virtually zero GHG emissions but the production cost needs to be decreased significantly to be competitive with more mature pathways based on fossil hydrocarbons[48] (grey hydrogen).

Sustainable production of hydrocarbons and derived materials would require emission-free hydrogen. Hence a fundamental consideration for CCU is the hydrogen source and its carbon footprint. If water electrolysis is fuelled only by fossil energy (yellow hydrogen), then it is in fact likely to have an overall carbon footprint larger than conventional grey hydrogen. As most countries still use some fossil resources in their electricity production, the grid power could not be considered fully emission free. Green hydrogen would in such cases either need direct connection to, for instance, a wind park or certification of the sustainability benefits by a third-party LCA.

Blue hydrogen

In principle, the production process for blue hydrogen can be identical to hydrogen produced from natural gas by dry or steam reforming (grey hydrogen), but with the additional step that virtually all the fossil carbon is captured and permanently sequestered. There are also processes in development where the reforming step and the CO_2 capture is fully integrated (Andresen et al., 2014). In practice, however, the complete CCS process is not 100%. Although the carbon footprint may potentially be lower than 1 kg CO_2e per kg hydrogen produced (DNV, 2021), blue hydrogen is classified as "low-emission hydrogen" in the EU nomenclature, in contrast to green hydrogen which can be "*renewable*" provided that the electrical power is fully renewable.

Blue hydrogen depends on access to natural gas, as well as opportunities for CO_2 sequestering. The US Inflation Reduction Act offers public support for building CCS sites linked to natural gas wells and tax incentives for use of blue hydrogen. In Norway there are plans for blue hydrogen production at the current oil and gas refinery at Mongstad, which is only 40 kilometres from the Norther Lights CCS hub. However, hydrogen is difficult to transport over long distances, hence for central European markets it might be better to transport natural gas from the North Sea in existing pipelines, extract the hydrogen close to its use, and then transport the CO_2 back for storage, rather than transporting the final hydrogen product to the market.

National hydrogen strategies

Given the general utility and importance of hydrogen in a net-zero scenario, many countries have developed a dedicated hydrogen strategy. Table 4.2 provides an overview of several OECD member states that have already a national strategy in place, while others are in the process of doing so.

Table 4.2. National hydrogen strategies of selected OECD countries

Country and year	Source	Policy implications
Australia, 2019	www.industry.gov.au/data-and-publications/australias-national-hydrogen-strategy	Rapid scale-up strategy; Identifies 57 joint actions, Capacity building; 'Responsive' regulation; Industrial feedstock; Heating; Heavy transport; Lon-term governance structures; Safety
Canada, 2020	www.nrcan.gc.ca/climate-change/canadas-green-future/the-hydrogen-strategy/23080	New H_2 supply, distribution infrastructure; Drive investment through regulation; Key enabler for net-zero emissions, 2050; Engage indigenous communities; Create 250 000 jobs; Energy resilience
Chile, 2020	https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf	Emissions reduction; Greening industry; Local jobs; Public-private partnerships; Create electrolysis sector; Energy exports; Competitive production; 6 priority applications; Standards, safety; Governance
France, 2020	www.economie.gouv.fr/presentation-strategie-nationale-developpement-hydrogene-decarbone-france	R&D&I; Scale-up barriers; Electrolyser sector; Heavy transport; Skills; Energy security; Local; Regional; 11 key markets; Clean mobility; Jobs; Deployment; Decarbonise; Defossilise; Europe; Infrastructure
Germany, 2020	www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html	Market creation; Technology rollout; Offshore and onshore; Security; Alternative energy; Chemicals, steel sectors; transport infrastructure; Skilled labour; International markets; Create National Hydrogen Council
Hungary, 2021	https://cdn.kormany.hu/uploads/document/a/a2/a2b/a2b2b7ed5179b17694659b8f050ba9648e75a0bf.pdf	Action plan; Target system; Decentralised; Industry decarbonisation; Electrolyser capacity building; Green transport; Electricity infrastructure; Regulation, International cooperation, R&D&I, Skills, education;
Italy, 2021	www.mise.gov.it/images/stories/documenti/Strategia_Nazionale_Idrogeno_Linee_guida_preliminari_nov20.pdf	Electrolyser capacity; Green H_2; 10 000 jobs; Transport; Chemicals; Market costs; Emissions; Regulation; Standards; Investments; Refineries, Ammonia, Iron/steel, H_2 corridors; Infrastructure; R&I
Japan, 2017	www.meti.go.jp/english/press/2017/1226_003.html	Cost-competitive with fossil; Energy security; Emissions reduction; Heat; Power; Industry processes; Transport; Safety, Supply chains; Pipelines technology; Standards; International cooperation; Public support
Korea, 2019	www.korea.kr/special/policyCurationView.do?newsId=148857966#L4	Scale-up; Vehicles; Power; Heating; Imports; Economic growth; Safety; Regulation; R&D; Standards; Market; Financing and investments; Competitiveness; Energy security; Roadmap; Infrastructure

Netherlands, 2020	www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen	National Climate Agreement; Clean H_2; Job creation; Scale-up; Cost reduction; PPP; Global market; Air quality; Supply chain; Clusters; Regulation; Safety; R&D&I; Regional; International strategy
Norway, 2020	www.regjeringen.no/contentassets/8ffd54808d7e42e8bce81340b13b6b7d/hydrogenstrategien-engelsk.pdf	Value creation; CO_2 tax; Demonstration; Piloting; Value chain; CCS; Electrolysis; Competitive; Safety; Standards; Zero Emissions Fund; Maritime; Public procurement; International collaboration; ETS
United States	www.hydrogen.energy.gov/clean-hydrogen-strategy-roadmap.html	Scale-up; Safe storage; Levelised cost; Permitting; Decarbonisation; Supply chain resilience; Codes; Standards; Jobs; Training; Private investment; Chemicals; Steelmaking; Transport; Electricity; RDD&D; Holistic; Justice; Regional hubs; Electolysers, Regulation
European Union, 2020	https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf	Emissions reduction; Air quality; Achieve Green Deal; Decarbonise; Deployment, Investment; Electrolysers; Lead markets; PPPs; Market; Carbon capture; Investment; Clean Hydrogen Alliance; Roadmap 2050;

Note: The selected policy implications for each country are not exhaustive. They demonstrate the range of policy issues at stake and highlight commonalities and differences.

One of the general observations from the national strategies is that many envisage multiple roles for hydrogen, although the timescales for deployment vary (Table 4.3). A quite common objective is to provide the means to reach national climate obligations, for instance low-emission solutions in the transport sector. This may include using hydrogen directly in a fuel cell or indirectly by CCU-based production of so-called synthetic fuels for heavy vehicles, aviation or the maritime sector. Other aspects may be related to sustainability goals in specific domestic industry sectors, such as steel, cement, ammonia, or organic chemicals.

Table 4.3. Sectors prioritised in national hydrogen strategies in selected OECD member states

Sector	Priority in National Hydrogen Strategy										
	Australia	**Canada**	**Chile**	**France**	**Germany**	**Hungary**	**Japan**	**Korea**	**Netherlands**	**Norway**	**European Union**
Heating	Immediate	Immediate	Immediate	Lower	Lower	Immediate	Immediate	Lower	Immediate	Lower	Lower
Industry:											
Iron/steel	Long term	Immediate	N/A	Immediate	Immediate	Long term	Lower	Lower	Immediate	Lower	Long term
Chemical feedstock	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Lower	N/A	Immediate	Immediate	Immediate
Refining	N/A	Immediate	Immediate	Immediate	Immediate	Immediate	Lower	N/A	Immediate	Lower	Immediate
Other (e.g. cement)	N/A	Immediate	N/A	Immediate	Lower	Long term	N/A	N/A	Lower	N/A	N/A
Power generation	Lower	Lower	N/A	N/A	N/A	Lower	Immediate	Immediate	Lower	N/A	Lower
Transport:											
Light vehicles	Lower	Immediate	Long term	Lower	Lower	Long term	Immediate	Immediate	Immediate	Lower	Lower
Medium, heavy	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Long term	Immediate	Immediate	Lower	Immediate
Buses	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Long term	Immediate	Immediate	Lower	Immediate
Rail	Lower	Long term	N/A	Immediate	Immediate	Lower	Lower	Lower	Immediate	N/A	Immediate
Marine	Long term	Long term	Long term	Lower	Long term	Lower	Lower	Lower	Lower	Immediate	Long term
Aviation	Lower	Long term	Long term	Immediate	Long term	N/A	Lower	N/A	Lower	Lower	Long term

Note: N/A = not applicable
Source: Adapted from World Energy Council (2021)

Hydrogen policies for chemicals, materials, and fuels

The policy analysis provided in Table 4.3 shows the importance of hydrogen in manufacturing of chemicals. Saygin and Gielen (2021) argued that green hydrogen is essential for the chemicals industry to reach 2050 targets. On the basis of this analysis, chemical feedstock is jointly the top sector where 'immediate' action is needed.

While the technology for both green and blue hydrogen already exist, the current global production is still low, about 3 megatonnes of blue and only 260 kilotonnes of green hydrogen[49] of a total demand of 15 megatonnes. As alluded to, the current costs of both green and blue hydrogen are considerably higher than for traditional 'grey' hydrogen. Cost-competitiveness is a major issue today and for some time into the future. Driving down costs will require a range of supply- and demand-side instruments. On the demand-side, markets need to be incentivised and developed. That will require standards and robust regulation and governance. Green procurement is another market-based mechanism of interest.

Electrolysis makes it feasible for multiple countries to produce their own hydrogen. It is inevitable, however, that some countries will have national advantages, although the success formula can be complex. Countries in the Middle East may for instance benefit from an ample supply of relatively cheap sun energy but will also need stoichiometric amounts of pure freshwater not so easily available.

Apart from the cost, the availability of electricity for green hydrogen production will have to compete with alternative use of the renewable power. If a country has a plan to build economic growth around CCU and does not have the renewable energy capacity, the cost of infrastructure for hydrogen import must be included, which can be considerable. Gas-for-Climate (2021) is an informative document describing hydrogen infrastructure and financing plans in various European countries.

As synthetic chemicals and fuels require large investments, a clear regulatory framework is essential, particularly with respect to demand-side measures. This is illustrated by the efforts to stimulate sustainable aviation fuel (SAF) in Europe. As part of their "Fit For 55" programme, the European Commission has announced ambitious blending mandates, rising from 2% SAF in 2025 to 20% in 2035 and 70% in 2050[50] (Refuel EU). Of this there is a proposed sub-mandate of synthetic SAF (35% in 2050), which would depend on hydrogen. However, to qualify as synthetic SAF, only green hydrogen made from fully renewable energy would be allowed[51].

Korea acts as an exemplar of policy to develop a hydrogen ecosystem. For Korea, the ambitions are large and a little different from other countries in the emphasis on transportation and power generation (Box 4.2). It also illustrates the need to align demand side ambitions with realistic supply side opportunities.

Box 4.2. Korea's hydrogen economy policy

For much of this century so far Korea has been investing in hydrogen through both the public and private sectors, resulting in a maturing industry targeting mobility and power generation in near term. This has been achieved by a policy mix designed to attract many companies that have formed the Korean hydrogen ecosystem. It is estimated that there are almost 400 companies in the Korean hydrogen industry.

Korea's hydrogen policy portfolio

Master Plan for an Environmentally Friendly Hydrogen Economy—Visions (2005)

This set targets of 3% for the share of hydrogen in final energy, supply of two million hydrogen vehicles (8% of all vehicles), and 6.8% for the share of fuel cells for power generation in total power demand. Korea proved ahead of its time, and the plan never met its targets, one reason being a lack of international interest.

Strategic Investment Direction for Innovative Growth (2018)

The Korean government selected the hydrogen economy as one of three major strategic investment areas.

Hydrogen Economy Activation Roadmap (2019)

During 2018 a national committee prepared a roadmap, which was launched in 2019, establishing three main policy directions to realise the hydrogen economy:

1. Create an industrial ecosystem around hydrogen vehicles and fuel cells.
2. Build a production capacity of 5 million tonnes hydrogen by 2040.
3. To prepare and implement safety management standards for hydrogen.

Act on Hydrogen Economy Development and Hydrogen Safety Management

The Hydrogen Act makes provisions for hydrogen equipment safety requirements, certification processes and the roles and responsibilities of various government agencies. The controlling body is the Hydrogen Economy Committee chaired by the Prime Minister and with ministers from eight ministries.

Green New Deal (2020)

Out of the KRW 74 trillion (USD 56 billion) of total capital investment under the Green New Deal, the largest portion, KRW 20 trillion, is to be used for green mobility, particularly hydrogen projects.

Source: Department of International Trade (UK) (2021); Youngok et al. (2022)

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5

Case study summaries and their main policy points

This chapter presents sixteen case studies submitted by nine OECD member states. They are summarised and include the policy issues raised by the authors of the case studies. This list of case studies provides an insight into the extent to which hybrid technologies, involving more than one single technology, will be important in the net-zero carbon landscape later this century.

The table below summarises the sixteen case studies submitted by nine OECD member states.

Table 5.1. Case studies of carbon management technologies

Country	Case study	Main technology	Convergence?
Austria	Carbon2Product Austria (C2PAT): capturing and using CO_2 from cement production	Nanotechnology	Chemistry, photovoltaics
Canada	Brock Commons timber-framed high-rise building	Construction materials	Chemistry, wood technology
	Toundra Greenhouse - Turning waste and emissions into food with the circular bioeconomy	Bioenergy with carbon capture and utilisation (BECCU)	Waste heat capture, digital, water recycling
	Innovation challenges as funding mechanisms to accelerate emerging CCUS technologies	Funding mechanisms for any CCUS technology	Convergence is not specifically targeted but is not excluded
	Solid recovered fuels and CCUS in industry	Waste-to-energy facilities that use SRFs with CCUS technologies e.g., gasification	Waste recycling
Germany	ZeroCarbon FootPrint (ZeroCarbFP): Conversion of carbon-rich waste streams for a sustainable, biological synthesis of valuable substances	Biotechnology, chemistry	Waste recycling
Italy	Compostable bioplastics value chain	Biotechnology, chemistry	Industrial composting
	PlaCE: (Offshore) Platform conversion for eco-sustainable multiple uses	Offshore rig decommissioning, mineral accretion, aquaculture, solar energy	Life-Cycle Cost-Benefit, CCUS, renewable energy e.g., hydrogen production / storage
Japan	Carbon capture and utilisation by Saga City incineration plant	Chemistry	Renewable energy, incineration
	Recycle system development of municipal and industrial waste to useful raw chemicals	Biotechnology	Chemistry, gasification
Korea	Sustainable chemicals and fuels production using nanotechnology in Korea	Nanotechnology	CCU, chemistry
Norway	Production of fish feed by gas fermentation	Biotechnology	Aquaculture, CO_2 capture, water electrolysis for hydrogen production
	Decarbonisation strategies of a ferrosilicon plant	Biotechnology	CCU, CCS, chemistry
United Kingdom	Captured CO_2 for new fertilizers	Chemistry, biochemistry	Agricultural technology
United States	Digital agriculture: soil organic carbon networked measurements technologies	Digital, ICT	Agricultural technology
	Hybrid technologies for recycling waste carbon using gas fermentation and upgrading	Biotechnology	Catalysis, bioenergy

Several other observations are worth noting that are not implicit from the case study summaries.

- Some of the case studies address the industries that are considered to be the hardest to abate, in particular chemicals, cement, steel, aviation.
- Renewable energy is frequently used as the energy source. In particular, several of the countries that submitted case studies are planning for a hydrogen economy to fuel these technologies. This net-zero carbon future will go hand in hand with hydrogen, resulting in the need for high levels of investment in both manufacturing and energy technologies. While energy and transportation policy is relatively mature, this is not the case for hydrogen or the other sectors highlighted in the case studies.
- Biomass features in the majority of the case studies. One of the case studies concerns funding mechanisms and is exempt from this calculation. Of the fifteen other case studies, thirteen either

directly or indirectly involve biomass, but are not necessarily biotechnology-based projects. Examples are the use of wood in high-rise building construction (direct) and digital agriculture (indirect). This is highlighted because some of the most controversial policy issues raised in this report arise from biomass utilisation and its connection to land use, perhaps the greatest source of policy dilemmas and trade-offs. The use of other feedstocks like waste gases and chemically recycled plastics relieve pressure on land but have their own policy issues.

- The policy issues that are raised are many, and most are familiar to innovation policy makers. In many cases, the technologies are designed to replace an existing technology, usually of fossil or mineral origin, that is very well established in the market. The driving force is sustainability more generally, and more specifically reduction of emissions. As described elsewhere, that creates dilemmas for policy makers.

Soil as a resource is often forgotten or under-valued, and yet, as mentioned, land use is the most controversial and complex of policy issues. Several of the case studies have an emphasis on improving soil quality, recognising its place as the resource most important to the existence of humans, as without it there is virtually no food. Soil is also an enormously important carbon sink but also, due to human exploitation practices, can contribute to a large proportion of global warming potential.

Austria: Carbon2Product Austria (C2PAT)

Summary

In the cement industry, a large proportion of CO_2 emissions cannot be avoided. As it is crucial to find ways to reduce the emissions form the cement industries, the Carbon2Product Austria (C2PAT) project proposes a novel pathway for the utilisation of unavoidable CO_2 emissions. By capturing CO_2 from cement production, processing that CO_2 and using it as a resource, the project aims at demonstrating a first-of-kind, cross-sectoral carbon value cycle at industrial scale and promoting climate neutrality in Austria.

The overall system is based on the integration and joint operation of different technologies that will be combined into one novel hybrid technology and a holistic value cycle. A facility cluster will be installed by 2025 at the site of Lafarge's cement plant in Mannersdorf. This cluster will comprise a carbon capture unit, a new photovoltaic (PV) park operated by VERBUND, water electrolysis for the production of green hydrogen, a new synthesis route using reverse water-gas shift reaction (RWGS) and a low-temperature Fischer-Tropsch synthesis unit. Intermediates will be processed at OMV/Borealis sites into olefins and ultimately renewable-based plastics. The demonstration plant will also provide important technical insights and information that will ultimately lead to the construction of an industrial full-scale plant by 2030.

Public intervention and supporting policies

In order to address potential sustainability dilemmas and to bring the C2PAT business case and similar ones to fruition, **a sustainability framework is needed**. This framework has to consist of a combination of different building blocks. On the one hand, these building blocks have to address the supply side: **quotas for the share of CO_2-neutral products** offered or produced are needed. Sustainable and long-term incentives and mechanisms are needed to keep the products constantly in the market. These could include e.g., **CO_2 trading certificates** or **adequate CO_2 pricing** that really covers external effects. Moreover, **LCAs should be made mandatory** for certain products to capture all impacts throughout their life cycle and enable communication of the results accordingly.

Regarding green energy and hydrogen technologies, there is a need for **public funding to address potential environmental sustainability dilemmas** e.g., land-use change. Additionally, it is essential to **establish global sustainability standards** for energy and hydrogen production incorporating the SDGs.

These standards will create a common, international understanding and should provide a basis for creating international regulations for the import of green energy and hydrogen for the future electrification of different sectors. As a final important component, to assure the successful implementation of CCUS technologies, the **creation of regulatory measures** is needed, which must enable competitiveness against fossil-based products/materials, economic viability and the adoption of new energy systems.

On the other hand, there are certain elements that are necessary for the demand side: there is definitely a need for **regulations as well as incentives to push the demand side**, such as **carbon footprint labelling, tax reductions or credit schemes**. The trend that customers are increasingly willing to spend more money on CO_2-neutral products can be supportive in this regard. However, this positive attitude on the part of customers is not always the case: measures are clearly needed to **increase public acceptance**. Public discussions need to be initiated that address potential environmental sustainability dilemmas and **increase the understanding for higher-priced CO_2-neutral products**, corresponding innovations and required **behavioural changes** in consumption and lifestyle. The C2PAT project will also contribute to building up this necessary framework for CCU and CCS technologies. There will be a 'regulatory group' in the project, which will develop practical requirements and actions for Austria, but also for Europe, on the basis of the demonstration plant.

Canada 1: Embedding carbon in the built environment

Summary

The University of British Columbia (UBC) Brock Commons student residence building is an 18-storey wood hybrid building built in 2013. The building is 17 storeys of mass-timber built on a one-storey concrete podium, with two concrete staircases, and cost CAD 40.5 million to build. Each floor is made of five-ply cross-laminated timber (CLT) with the building columns made of glue-laminated timber (GLT). Some 2 233 m^3 of Canadian timber was used to construct the building, saving approximately 2 432 tonnes of CO_2 from being emitted, with 1 753 tonnes of CO_2 sequestered in the timber itself, and 679 tonnes of CO_2 avoided in substituting traditional construction materials with low-carbon wood materials. It was built in 70 days, approximately four months faster than projects of similar size using traditional construction materials.

Public intervention and supporting policies

The project was supported with funding from the Canadian federal government under Natural Resources Canada's Tall Wood Building Demonstration Initiative[1], as well as funding from the provincial government of British Columbia.

The building was designed to **maximise fire protection** for occupants, a common concern regarding mass timber buildings. It was also designed to meet the Leadership in Energy and Environmental Design (LEED) gold certification, a **sustainability accreditation system** that recognises environmental stewardship in building design and operations. Mass timber buildings are expected to provide **new socio-economic opportunities** across the supply chain, from harvesting to manufacturing facilities, as well as forest-based communities.

Canada 2: Using innovation challenges as funding mechanisms to accelerate emerging CCUS technologies in Canada

Summary

CCUS technologies are relatively nascent with few industrial scale commercial plants in operation today. While private-public partnerships have been effective in the development and demonstration of some flagship CCUS projects in Canada, significant research and capital is still required to help **de-risk these new technologies for private investors**. To help **address investor hesitancy** in CCUS technologies, recent innovation models centred on 'Challenges' and 'Prizes' have become popular among both private and public organisations to help spur innovation. These innovation challenges typically put forth a broad technological challenge or goal to the public with the best technological advance awarded prize money. Typically, these challenges are open to academics, start-ups, and SMEs that have developed new technologies that could address the challenge.

Public intervention and supporting policies

To date, three CCUS innovation challenges have been made available in Canada by both private and public actors: the USD 20 million Carbon XPRIZE[2] by Natural Resources Group and Canada's Oil Sands Innovation Alliance (COSIA), the CAD 35 million Emission Reduction Alberta (ERA) Grand Challenge[3] by Emissions Reduction Alberta, and the CAD 13 million Sky's the Limit Challenge[4] by Natural Resources Canada. All three competitions have been part of a broader initiative to support the development, scale-up and commercialisation of CCUS technologies in Canada.

CCUS potential, and the speed of its deployment, will likely still require some government funding and intervention to **further de-risk CCUS technologies**. However, innovation challenges can also do this, limiting the need for government funding and still accelerating technological development and deployment. In addition, supporting government frameworks, strategies or policies, like Canada's CCUS strategy that is currently in development, can **send important investment signals to private investors and help further de-risk investment** in new and emerging technology.

Canada 3: Turning waste and emissions into food with the circular bioeconomy

Summary

The Toundra Greenhouse in Saint-Félicien, Quebec is a 27.5 hectare greenhouse complex. It uses bioenergy carbon capture and utilisation (BECCU) technology to capture up to 30 metric tonnes of CO_2 per day (11 000 tonnes of CO_2 annually) from the neighbouring sawmill's cogeneration heat and power (CHP) plant. The captured carbon is transferred directly to the greenhouse to grow upwards of 45 million cucumbers per year. The greenhouse also captures waste heat from the neighbouring CHP plant to heat the greenhouse throughout the year and has a specially built lagoon to capture rainwater and snow melt to water the cucumbers throughout the year.

The greenhouse was built in 2016, and expanded in 2020, costing CAD 100 million dollars. The greenhouse was part of an initiative to improve food security in the region as well as improve the circularity of the CHP plant. The greenhouse also provides important socio-economic benefits to the region by providing employment opportunities, with more than 100 people currently employed to maintain and operate the greenhouse, as well as improving the resilience of the local supply chain.

Public intervention and supporting policies

The project was supported with CAD 3 million in funding from the Canadian federal government and CAD 5 million in funding from the Quebec provincial government. It supports **decarbonising Canada's natural resource sector** while providing new **economic opportunities for rural communities** in Canada.

Canada 4: Using Solid Recovered Fuels and CCUS in Industry

Summary

Solid recovered fuel (SRF) is biogenic (e.g., scrap wood, paper) and non-biogenic (e.g., plastic) feedstock sourced and sorted from non-hazardous municipal solid waste (MSW) and used as a feedstock in various applications. More specifically, SRFs can be used in processes such as gasification to produce energy and chemicals, with the added benefit of improving waste management, especially in large urban areas. In addition, unlike unsorted MSW used in waste-to-energy facilities, which can include contaminants requiring specialised treatment, SRFs can be used in both pre-existing waste-to-energy facilities, as well as less capital-intensive facilities that do not require extensive flue gas treatment because it is a standardised, non-hazardous feedstock. Furthermore, pairing waste-to-energy facilities that use SRFs as a feedstock with CCUS technologies could help to achieve multiple sustainability objectives, such as improving waste and plastics management, while simultaneously improving/reducing the life cycle emissions associated with energy, fuels and/or chemicals production.

Another application of SRFs in current infrastructure includes using them for controlled combustion and displacing fossil-based fuels to reduce emissions in high emissions industries. For example, using SRFs as an alternative fuel paired with CCUS technology in cement kilns could help improve waste management in selected regions while significantly reducing the GHG emissions in the cement industry. Pairing waste-to-energy facilities and heavy industry that use SRFs with CCUS technologies could help make some industries or sectors net-neutral or net-negative, improving the overall carbon management of a number of industrial sectors.

Public intervention and supporting policies

The potential for such a set of processes to make a significant impact is dependent upon several highly variable factors, including **sufficient funds for innovation** in CCUS, emerging **policies to drive the use of alternative feedstocks**, and **public support for waste-to-energy facilities**. In addition, technology for waste-to-energy facilities may need to be **de-risked further to incentivise further private investment**.

Germany: ZeroCarbon Footprint (ZeroCarbFP)

Summary

By developing innovative products and systems with high potential for added value, the change from a fossil to a bio-based industry is promoted. One of the selected innovation alliances to boost this is ZeroCarbon FootPrint (ZeroCarbFP). ZeroCarbFP aims for the conversion of carbon-rich waste streams into valuable products and thus contributes to a sustainable carbon management. The use of alternative raw materials supports the greater independence from fossil feedstock by having a positive effect on cost structures and competitiveness. Thereby, the alliance takes up a central innovation topic for politics, economy and society, like protection of arable land for food production, the sustainable use of waste streams as a source for carbon, closing of cycles (cradle-to-cradle) by the circular economy. Furthermore, the cross-alliance doctorate programme UfIB - Bioeconomy Initiative Promoting Implementation will strengthen the next generation of scientists and link academia and industry in the development of sustainable production routes.

The sub-programme 1 Bioplastics of the ZeroCarbFP alliance is highlighted. In this sub-programme CO_2 as sole carbon source for the production of mono- and dicarboxylic acids as precursors for biopolymers (focus: succinic acid as monomer for biodegradable bioplastics) is addressed. In this sub-programme, microbial fixation of CO_2 is researched. A two-stage fermentation has been developed which converts CO_2 and hydrogen gas into acetate and succinic acid. The process can be coupled to an existing bioethanol plant, capturing the emitted CO_2 from fermentation. This eliminates the need to compress and transport CO_2 and enables the cascading use of CO_2. The hydrogen can be produced on-site by electrolysis powered by renewable electricity. Using waste and side streams adequately as a starting material leads to an overall higher material efficiency, reduces the dependency on critical raw materials and increase the flexibility of production sites.

Public intervention and supporting policies

The projects under ZeroCarbFP are funded by the German Federal Ministry of Education and Research (BMBF). Initially, ZeroCarbFP had a total budget of EUR 48 million and a time horizon of nine years, which was split into a research, a development and a piloting phase. The programme started in July 2013 and is planned to finish in March 2024.

Italy 1: Bio-based, biodegradable and compostable bioplastics for organic recycling and the creation of compost

Summary

Organic waste can be a valuable source of nutrition for soils. The development of a biodegradable and compostable plastic value chain (products such as bags, packaging, or cutlery) together with an efficient system for biowaste collection and recycling, can create a mixed waste suitable for organic recycling and for the creation of high-quality compost, to be used as a soil improver. The case of the city of Milan is a key example of the efficiencies that biodegradable and compostable materials can provide in the waste management system.

This case study is based on bioplastics that, other than being biodegradable and compostable, are also produced from renewable resources. This contributes to EU climate ambitions: by reducing emissions; by replacing fossil-based materials and energy with bio-based ones, notably biomaterials, and biochemicals; and by facilitating the use of compost in agriculture. It also prevents organic waste from ending up in a landfill, a practice that will be prohibited in the European Union from January 2024. The construction of integrated industrial and agricultural value chains is one of the central elements of the model to promote the sustainable use of biomass, contributing to soil protection and health.

Public intervention and supporting policies

The project is **coherent with the main EU and Italian legislative acts** related to sustainability and to the promotion of circular bioeconomy and biodiversity protection, such as: the European Bioeconomy Strategy[5]; the Italian Bioeconomy strategy; the new Waste Directive[6]; the Green New Deal[7]; the Farm to Fork[8] strategy, the Next Generation Europe and the Italian Recovery and Resilience Plan (PNRR); and the latest Best Available Techniques (BAT) and the new regulation on fertilizers.

Also required is **promoting incentives** within the Common Agricultural Policy (CAP) and the Climate Change and Horizon Future agreements for the return of resources to agriculture, for the maintenance of soil quality and fertility, decarbonisation and the use of biodegradable products.

Italy 2: PON-Platform Conversion for Eco-Sustainable Multiple Uses (PlaCE)

Summary

Decommissioning of offshore oil and gas infrastructures involves removal of large tonnages of materials to be dismantled and recycled. Rather than remove them completely, offshore oil structures can be used to support marine communities, in some cases of regional significance. Materials, structures, power connection to shore could be instead reused and become an advantage for new installations rather than waste. In this context, an experiment in reusing an offshore platform destined to be decommissioned started in 2020, funded by the PON-FESR project 'PlaCE: Platform Conversion for Eco-Sustainable Multiple Uses'[9] and is still ongoing. The platform is Viviana 1, operated by Eni Spa, placed offshore of Pineto in a 21-metre water depth, in front of the Abruzzo Region, at the Central-East side of Italy.

The scope of the project is to demonstrate the added value of the multiple uses of marine areas and to promote its replicability starting from the reuse of existing platforms. Based on the local climate conditions, the selected reuse solutions are a set of innovative eco-sustainable strategies for offshore aquaculture, solar panels for power independence of the platform activities and the life extension of the offshore infrastructure based on mineral accretion technology under low voltage electrolysis to protect the platform's steel jackets from corrosion. Besides the field activities, the demonstration project prompts the optimisation of marine renewable energy integration, the set-up of business models and the replicability in other sites to extend the range of economic activities. Overall, the case study boosts the blue circular economy by cost-sharing technologies and logistics and by reusing existing structures.

Public intervention and supporting policies

PlaCE is a PON project (Programma Operativo Nazionale Ricerca e Innovazione)[10], supported by the Italian MIUR (Ministry of Education, University and Research). The project budget was EUR 9 114 177. More information is available at the project portal[11].

Japan 1: Recycle system development of municipal and industrial waste to useful raw chemicals

Summary

This case study concerns a system of waste treatment to useful chemicals developed by Sekisui Chemical Co using a microorganism by LanzaTech. Various kinds of waste generated from homes and factories are used as carbon feedstocks. They are gasified to generate hydrogen and carbon monoxide (CO), and then converted to ethanol using anaerobic fermentation technology. The produced ethanol can be used as fuels or solvents or can be used as raw material for ethylene and produce polyethylene or used in various chemical industry fields. Between 2014 and 2018, a pilot study to prove the concept was carried out by running the facility of 10 000 litres per year from gasified waste. Currently, a demonstration facility capable of treating 20 tonnes per day of waste is under construction for operation to start in 2022. In the future, a vision to realise a circular ecosystem on a community-by-community basis, aiming for processing capable of 200 tonnes per day or more (equivalent to the waste generated by 200 000 people per day), will be constructed in Japan and elsewhere.

Public intervention and supporting policies

It is necessary to **support the demonstration** of feasible implementation at the municipal level in terms of cost and operation. In addition, when the facility is installed at multiple locations, it is necessary to **provide an education programme** for operations. The cost competitiveness is currently weak against fossil resource-derived products. Therefore, **direct support such as subsidies, taxation such as carbon pricing, fossil usage restrictions**, are useful. Indirect support from multiple perspectives such as **regulatory aspects and standards** such as ISO and **green labels** should be effective. It is also useful to expand the use of private sector vitality for public works projects using private finance initiatives or other monetary mechanisms to address the issues of local governments.

Japan 2: Efforts of CCU by the Saga City cleaning plant

Summary

Saga City is the first city in Japan to separate and recover CO_2 from part of the exhaust gas generated during waste incineration, and to use it in the CCU project to cultivate microalgae that produce raw materials for cosmetics and other products, and to cultivate agricultural crops. The facility for separating and recovering CO_2 (CCU facility) has been installed at the Saga City cleaning plant and has been in operation since August 2016. Currently, around the Saga City cleaning plant, there is a concentration of industries using waste biomass-derived CO_2 as a resource that will contribute to the formation of a decarbonised society and the creation of employment. Saga City, which was certified as a biomass industrial city in 2016, aims to become "*a city where what used to be waste is recycled while creating value as energy and resources*", and the CCU project is one of the projects to realise this future vision.

Public intervention and supporting policies

Policy instruments, such as **public procurement and subsidies**, can be used to encourage the creation of markets for products using waste biomass-derived CO_2 and the introduction of equipment to capture the CO_2 used in their production. The involvement of the public (local government) is essential for the CCU project at the waste treatment plant because it uses local environmental infrastructure, and that environmental infrastructure carries a negative image. In addition, public involvement is also required for the handling of the separated CO_2 (storage or utilisation). In particular, in the case of CO_2 utilisation, the involvement of government is necessary because there may be restrictions under existing laws depending on the business development. In addition, direct support, such as subsidies, is effective in developing CCU technology in Japan. Saga City's CCU project has received support (**subsidy**) from the Ministry of the Environment for the construction of the facilities, and the relevant ministries have cooperated in **clearing the legal hurdles for the industrial use of CO_2**.

Korea: The transition towards a carbon-neutral economy: Sustainable chemicals and fuels production using nanotechnology in Korea

Summary

This project is focussed on technologies to produce sustainable chemicals and fuels from captured CO_2 emitted by the oil refinery process. A large proportion of heavy industries such as steel, petrochemicals, oil refining, and cement emit large amounts of GHGs in Korea. The industry sector was estimated to be responsible for 37% of Korea's total GHG emissions in 2017.

The CCU Customised for Oil Refinery project aims for development and demonstration of an on-site CCU process with a scale of 1-10 tonnes CO_2 per day (TRL 6-7), including CO_2 capture technology for CO_2 emission sources in an oil refinery complex (e.g., fluid catalytic cracking unit), catalytic and electrocatalytic CO_2 conversion technologies to produce syngas and olefins, and fuels (gasoline, diesel, jet, etc.) production technology from syngas. The key technology of the project is nanotechnology for the development of high-performance CO_2 conversion catalysts to produce sustainable chemicals and fuels.

Public intervention and supporting policies

This case study provides an example of CCU innovation R&D project in Korea, a 'CCU Customised for Oil Refinery (2022-2025)' with a budget of USD 25 million supported by the Ministry of Trade, Industry and Energy (MOTIE).

In Korea, CCUS technologies were developed by Korea CCS 2020 Project with a budget of USD 150 million supported by the Ministry of Science and ICT for years 2011- 2020. The CCS technology developed in this project has been applied to a **multi-ministerial joint project** (USD 50 million, 2021-2023), and a large-scale integrated CCS demonstration project is currently underway.

Norway 1: Production of fish feed by gas fermentation

Summary

In this case study the enabling technology is bacterial fermentation using CO_2 as carbon source and energy from green hydrogen. The bacterium used is a naturally occurring strain of *Cupriavidus necator*, which has been extensively studied and is approved for food and feed applications.

The main sustainability objective is to replace soy as a protein ingredient in feed for aquaculture of salmon. Farmed salmon is the second largest export industry in Norway with an annual production of 1.35 million tonnes, requiring more than 400 000 tonnes of concentrated protein in the feed. The import of soy is the main source of CO_2 emissions within the salmon industry, both directly from soy cultivation, processing, and transport and indirectly from land-use change. Beside its negative climate effects, soy cultivation is seen as a major cause of deforestation and biodiversity loss.

For Norway, sustainably produced feed ingredients are key, not only to continue salmon farming at the current level, but for further expansion. So far, public measures to stimulate this industry have focussed on technology and innovation. This case study illustrates the interplay of several technologies creating a unique industrial ecosystem, comprising gas fermentation, advanced aquaculture, novel CO_2 capturing systems, and improved water electrolysis for hydrogen production.

Public intervention and supporting policies

In Norway, three main public facilitator organisations are cooperating to establish a pilot facility for gas fermentation. In 2016, Innovation Norway, the main government agency for industry development, took an initiative to map and describe opportunities in this field. Subsequently, SIVA, a funding body for research infrastructure, acquired an existing facility suitable for gas work, and the Norwegian Research Council provided a major grant to fund a first set of equipment. This open-access facility is now being administrated by NORCE with G2F as its first customer.

Norway offers several **national R&D funding programmes driving the green transition**, and several companies involved have received public support for their respective projects. This case study illustrates the importance of **grant mechanisms simulating complete value chain and cross-sectorial cooperation**. In 2021 the Norwegian government announced the ambitious goal that all feed should come from sustainable sources by 2030. Recently, sustainable feed has been defined as a national mission and development of a set of grant programmes and policies are in progress.

Norway 2: Decarbonisation strategies of a ferrosilicon plant

Summary

Finnfjord is a ferrosilicon producer located in northern Norway. While virtually all their electrical power consumption comes from hydropower, they are still dependent on fossil carbon as a reducing agent in their metallurgical process, leading to an annual emission of 300 000 tonnes of CO_2.

This case study is about Finnfjord's multiple strategies to become carbon neutral. In summary they have four options, and a particularly interesting aspect of this case study is the fact that all four strategies are actively pursued. A first option is to introduce bio-based carbon in their core process. Alternatively, the emitted CO_2 could be captured for permanent storage (CCS). This case study, however, is focussing on their two alternatives for CCU, which include one biotechnology project (cultivation of microalgae) and one chemical project (production of e-methanol).

Public intervention and supporting policies

The relative attractiveness of each alternative will depend on future market regulations and policy framework. The microalgae project depends on an early-stage technology; hence **technology risk is the main concern and public R&D grants are important**. Based on the potential value for the Norwegian aquaculture industry, Finnfjord has recently been offered a national grant of NOK 53 million or USD 5 million to further develop and test their microalgae process at full industrial scale. It is also expected that this funding will finance a detailed sustainability assessment.

The e-methanol project in contrast, is about deploying an already proven technology. While there is still technology risk in the actual process integration, for instance in energy optimisation, the dominating risks are regulatory, e.g., related to **future CO_2 emissions tax and potential market incentives for green methanol**. Given the inherent risk in first-of-kind projects, the Finnfjord/CRI/Statkraft consortium is applying for a flagship grant from the EU Innovation Fund.

The case study illustrates how public policies can influence the attractiveness of different industry options, thus steering the sustainability consequences and trade-offs. If the carbon tax is too high, CCS would probably be preferred. This would benefit climate, but not biodiversity. If, on the other hand, market incentives are strong, carbon recycling (CCU) would be more attractive, potentially reducing the pressure on bioresources. However, assuming a combination of high carbon tax and strong market stimulation, DAC may become a preferred option for future microalgae or e-methanol production, both from a commercial and a sustainability perspective.

United Kingdom: CCUS for Zero Carbon Fertilizer production

Summary

The study is of a commercialised technology for the production of net-zero carbon fertilizers to allow a wide range of businesses to generate commercial value from captured carbon and other agricultural and industrial waste streams while also delivering improved sustainability. It is now commercially viable without any government subsidies. It uses captured CO_2 from industrial power generation to stabilise a wide variety of materials (such as ammonia and phosphates) from agricultural and industrial waste streams and uses these to create new fertilizer products with significantly lower than usual carbon and resource footprints.

Public intervention and supporting policies

This technology is important in realising climate policy goals as it commercialises and incentivises capturing and converting waste, and it targets one of the most difficult decarbonisation sectors - agriculture, which currently contributes around 10% of UK greenhouse gases. The technology is fully commercialised and therefore relies on no UK government subsidies.

United States 1: Hybrid technologies for recycling waste carbon using gas fermentation and upgrading

Summary

The case study focusses on a public-private partnership (US Department of Energy and LanzaTech) for fermentation of waste gas to produce sustainable aviation fuel (SAF) while illustrating other opportunities for carbon recycling. Technologies for waste gas recycling include gas fermentation, which produces ethanol and other chemicals directly, and chemical catalysis. SAF is made by combining gas fermentation (biotechnology) with chemical catalysis in a specific hybrid process called Alcohol-to-Jet (ATJ). Such hybrid processes offer pathways to a broad range of carbon-based products from wastes.

In the first commercial plants to demonstrate this technology, LanzaTech used bacteria to produce ethanol from CO-rich steel mill or ferroalloy waste gases. That ethanol can then be converted to SAF using the ATJ process, which has been demonstrated on two commercial flights. Moving forward, a 10 million gallon per year ATJ production facility is under construction at LanzaJet Freedom Pines Fuels, LLC in Soperton, Georgia, USA, with support from the US Department of Energy.

Public intervention and supporting policies

On 9 September 2021 the US government announced new steps to **coordinate innovation** across the federal government, aircraft manufacturers, airlines, fuel producers, airports, and non-governmental organisations to advance the use of cleaner and more sustainable fuels in American aviation[12]. As a part of this effort, a new **Sustainable Aviation Fuel Grand Challenge** was announced to produce at least 3 billion gallons of SAF per year by 2030 and sufficient SAF to meet 100% of aviation demand by 2050[13]. Together, these announcements send a strong signal that decarbonisation of the aviation sector is a key piece of the broader US decarbonisation strategy.

An important driver for SAF is the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)[14] agreement that aims to lower CO_2 emissions on international flights to reduce contributions of the aviation industry to CO_2 levels. Adopted in 2016 with available **purchases of carbon credits to offset emissions**, CORSIA aims for carbon-neutral growth from 2020. Because another implementation option is a **procurement pledge by airlines for increasing volumes of SAF over time**, the private sector is working to develop processes to deliver SAF to meet an EPA finalised new rule to **set carbon emissions standards for airplanes** manufactured in the United States[15].

The US Congress is considering supportive policies including **grant programmes for the US Department of Transportation**, as well as **GHG performance-based tax credits**[16]. Other potentially impactful policies include the **US Renewable Fuel Standard (RFS)**[17] **which mandates alternative fuel production** through use of RINs (renewable identification numbers). To the extent that fuel pathways also sequester carbon through CCUS, **they may also be eligible for tax credits under section 45Q of the US tax code**. Sub-national policies such as **California's Low Carbon Fuel Standard (LCFS)**[18] are also important drivers for action as evidenced by the fact that nearly all SAF used in the US today is sold in the State of California.

In applied research and development**, industrial partners cost-share the government contribution at 20% (research) to 50% (development)**. In addition to research, the US government helps **mitigate risk for first-of-a-kind, clean energy projects through loan guarantees**. For example, the US Department of Energy supported the SAF development in this case study and supported the second-generation fermentation reactor that is currently at a pilot stage.

The US government also provides instruments that allow their national laboratories to work with industry including **Cooperative Research and Development Agreements** (CRADAs) and transferring technology from laboratories to industry. **Establishing technology-neutral policies is critical** and the policy must support the end goal. Finally, it remains important that **policy instruments support and allow broad licensing of the technology** in the United States and abroad.

United States 2: Digital agriculture: Soil organic carbon networked measurements technologies

Summary

Realising the potential for carbon-negative agriculture offers a significant step towards meeting US climate targets, including administration goals of a net-zero economy by 2050. Equally significant, however, is the ability to accurately measure this sector's contribution. Today's emissions monitoring, reporting, and verification (MRV) tools for agricultural carbon intensity (i.e., g CO_2-eq. per acre) comprise complex instrumentation, laborious sampling and analysis, and operational challenges (e.g., weather interference), which have restricted the resolution and fidelity of MRV outputs. If the broader bioeconomy is to deliver fully on its potential, there is an urgent need to better quantify the emissions footprint of natural systems so that it can accurately account for its economic and environmental impacts.

This case study is focussed on the US Department of Energy's SMARTFARM programme[19], a new experimental two-phase effort underway to advance agricultural measurement technologies and practices for carbon management. Focusing on biofuel feedstock crops, the programme is structured in two phases, with the first phase focussed on gathering high-resolution carbon intensity data using state-of-the-art tools and technologies (e.g., acre/sub-acre sampling, eddy covariance towers, soil chambers), and the second phase focussed on developing new metrology technologies capable of low-cost, low-uncertainty MRV of carbon intensity.

Due to the critical nature of agricultural outputs such as food, fibre, and fuel, the emissions associated with the sector have traditionally been accepted as the cost of doing business. The global carbon budget has now reached a point at which no sector can be left out of the drawdown equation. As the global economy shifts its ambitions from incremental carbon reduction to dramatic carbon removal, the agricultural sector has a unique role to play by offering relatively large-scale, low-cost, and, importantly, near-term sequestration; however, the sector cannot serve as a net sink without adequate incentives, and incentives are difficult to distribute without justification.

Public intervention and supporting policies

While technology solutions are needed to bridge the data gap in agricultural supply chains, there are several challenges that could prevent the distribution of much-needed financial incentives for agricultural carbon drawdown, including:

- **Protocols are varied in terms of contractual and MRV obligations, and available protocols lack rigor in terms of MRV,** which introduces uncertainty about the net carbon impact of enrolled farms. Though technology limitations place a major economic constraint on MRV options for these protocols - a constraint that the SMARTFARM programme seeks to eliminate - there is a broader question of how farmers are expected to access, compare, and securely enter agreements with carbon market developers.

- **Credit quality is varied in terms of uncertainty, additionality, and residence time.** This variation can make it difficult for credit buyers to know what they are paying for. While variation is likely to persist as carbon markets mature, clarity in what the crediting requirements are (i.e., degree of certainty, additionality, residence time) and how they are verified can help buyers make decisions and improve estimates of the sector's overall carbon impact.
- **Carbon drawdown requires new management tools and techniques,** which need to be proven in multiple cropping environments to evaluate efficacy and gain farmer acceptance. Farmer education about how and where to implement these practices can help to mitigate concerns and optimise implementation.

Public intervention through programmes such as SMARTFARM can bring **transparency, accessibility, and credibility** to the process of reducing agricultural emissions and increasing soil carbon uptake. These efforts, when combined with the resources of the private sector can provide a significant pathway to farmer acceptance and adoption of practices that optimise for yield and carbon intensity, paving the way for a reimagined agriculture sector that sequesters more carbon than it emits.

Notes

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6

Concluding remarks

This chapter highlights key aspects of the publication, focusing on broader sustainability issues and the risks of over-relying on biomass as a future feedstock. It emphasises the importance of a unified policy language, particularly in differentiating between CCU and CCS technologies, and stresses the need for careful evaluation of technologies ahead of the 2050 net-zero carbon deadline, highlighting the significant infrastructural changes required.

This publication is not primarily about climate policy

While climate underlies it, this publication is more about sustainability more generally, and about the realisation that biomass as a feedstock for the future cannot replace fossil carbon in its entirety. More importantly coming to overly rely on biomass could have serious negative repercussions for humanity and the planet. For this and other reasons, the short size of Definitions and terminology facilitate communication belies its importance. It is essential that governments, when formulating national policy but also when interacting with other governments, speak a unified language. It seems particularly relevant to 'CCUS' as CCU and CCS are very different. CCU, if deemed part of the climate and sustainability solution, will be heavily dependent on R&D subsidy for long periods. As this report demonstrates, the range of technologies of interest is very large, magnified by the emergence of hybrid technologies, and time is short.

Time and scale

A word that complements 'time' is 'scale', and the two are inextricably linked. As pointed out, 2050 is not far off, representing as it does about two innovation cycles for the chemicals industry. Any number of interesting laboratory studies can arise between now and then, and governments will be tasked with making tough funding decisions, assessing the commercial viability of technologies with limited information. A great deal seems to depend on rapidly developing renewable energy around the globe. Thus choice of technology paths to fund will depend on renewable feedstocks but also critically the energy burden. Let a critical message from this report be that net-zero carbon by 2050 involves a gargantuan scale of infrastructure change, much of it based on technologies not currently ready. Taking more time deciding technology paths by careful interrogation of the feedstock, energy and environmental implications will prevent expensive mistakes as global warming and its consequences continue.

History is the future

Henry Ford was famously unenthusiastic about history (Swigger, 2014). Thus we might airbrush from history that the Ford Model T, produced from 1908 to 1927, was an original flex fuel vehicle (FFV), being able to burn gasoline or ethanol. Or the fact that Ford produced a prototype car with bioplastic panels in 1941. The dominance of the internal combustion engine was settled with the conventional oil discoveries in the Middle East.

Some other pertinent lessons from history are directly related to the consumption of fossil resources. First, the fossil era ushered in a lifestyle unimaginable by many at the start of the 20th century. By mid-century, fossil resources began to shape and re-shape geopolitics. As the century began to wind down the complications of societies reliant on fossil resources began to emerge. By century end, the implications of weaponisation of fossil fuels and conflicts, and proof of climate change, had started the search for alternatives.

A more even distribution of renewable material and energy could change these dynamics. However, it is important that countries and their governments back new technologies to prevent being left behind. The transition is not simply all countries getting behind the climate crisis but is also about the other far-reaching social and environmental challenges identified. Planetary boundaries, a term born this century (Rockström, 2009) but still buried in the arcana of its professional cadre, may become mainstream as we learn to live within those boundaries.

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Carbon Management: Bioeconomy and Beyond

The bioeconomy brings opportunities for economic growth while tackling climate change. Fossil carbon resources can be replaced by bio-based carbon resources, especially biomass. To allow these solutions to be scaled up without threats to biodiversity and the environment, it is necessary to develop the bioeconomy as a circular economy. With this carbon management approach, other sources of carbon complement biomass: industrial waste, including gases such as CO and CO2, as well as physically and chemically recycled carbon. In the future, direct air capture (DAC) may become competitive and form part of the solution. These approaches can be considered 'circular' because they close material loops and keep carbon recycling in the economy rather than emitting carbon to the atmosphere. This report reviews a number of hybrid technologies that can be deployed to 'defossilise' economic sectors and sets out policy options to bring these technologies to commercial scale.

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