NEGATIVE EMISSIONS AND CARBON DIOXIDE REMOVAL (CDR) INCLUDING OCEAN SCENARIOS

Drivers, uncertainties, and deployment potential

BRIEF

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EXECUTIVE SUMMARY AND RECOMMENDATIONS

Negative emissions and Carbon Dioxide Removal (CDR) at scale is required to offset hard to reduce emission streams and remove historic emissions from the atmosphere. The more we emit cumulative before we reach net zero, the more we must take out from the atmosphere.

To meet the climate ambitions, the negative emission and CDR industry emerging must grow fast and become sizeable as will the need for permanent geological storage of CO_2 that comes with it.

CDR relies on and intervenes with the basics of earth systems such as the ocean, land, soil, and the atmosphere. This implies that CDR will need to be developed on terms that are acceptable to the natural systems which our human systems rely on.

The spatial consequences of CDR are very real and some solutions, especially arable nature-based ones, can come in conflict with e.g., land-use, freshwater usage and biodiversity if the land and/or the feedstock could be used for other purposes. The use of the ocean for CDR, on the other hand, opens new possibilities with less related conflict potentials.

Below is a snapshot into three CDR solutions that can make a difference at scale. These also represent the span of CDR technologies ranging from pure nature-based solutions, through hybrid nature-based/engineered solutions to fully engineered solutions and includes the ocean potential as well.

- **Seaweed farming** is the most promising ocean CDR solution. It uses the photosynthesis (it's for free) and the ocean (it's huge) for carbon removal. No soil, fertilizers, pesticides, fresh water nor any arable land is needed. Especially cultivation of fast growing, large kelp species like *Saccharina latissima* provides large scale biomass production with annual harvesting. The captured CO_2 can be stored permanently either at the sea bottom if deep enough or used as feedstock for BioEnergy with Carbon Capture and Storage (BECCS) plants or converted to biochar and distributed in the soil.

Off the coast of Norway, the estimated production potential is 20.000 tonnes seaweed (e.g., kelp) pr km² per year which again can capture 2500–3000 tonnes CO_2 pr km². Comparing this to Norway's total CO_2 release (49.3 mill tonnes CO_2eq in 2020), an area of 20.000 km² of seaweed farms can offset this whole amount. Norway has good natural conditions for such farms along most of the coast and especially offshore, where the temperature and nutrient supply is more stable than inshore.

Current seaweed production methods are labour intensive and high production costs indicate utilization of the biomass in more valuable end products like food and cosmetics than for CDR solutions. A thorough upscaling is needed along the whole value chain to reduce the costs and for this production methods that are more automized and mechanized must be developed and technology transfer from the offshore industries to biomass production should be looked for. Work on up-scaling of production with less labour-intensive technologies has just started. Since dried biomass is preferred both in BECCS and biochar production an integration with waste heat generating industries, preferably coastal ones, with CCS established, would ensure a more complete exploitation of the resources in new CDR value chains.

As of now there are no specific international rules for the different ocean CDR technologies, neither are there international instruments that deal with CDR, nor any specific guidelines on how to report negative emissions for ocean CDR. To succeed with ocean CDR at scale, this will have to be pushed for as well.

- **A BECCS plant** fuelled with sustainable feedstock in the shape of a waste-to-energy plant with CCS can be a low hanging fruit: It handles waste, produces energy, cuts emissions, and it can create negative emissions. The BECCS concept basically combines photosynthesis with carbon capture and permanent storage in external storage facilities. Regions with large forestry and forest industry, as e.g., Sweden, can provide feedstock to BECCS-plants without outtake of biomass. Here the BECCS-plants can be fuelled with pure leftovers (e.g., bark and treetops), and residues from the forest industry. Sweden has the potential to generate 30 mill tonnes negative emissions annually by BECCS. Their first large scale BECCS plant is due in production in the mid 2020-ies in Stockholm by Stockholm Exergi and will provide 800,000 tonnes negative emissions. It is partly financed by support from the EU Innovation Fund that is set up to stimulate demonstration of low-carbon technologies.

In Norway, Hafslund Oslo Celsio is planning to build the world's first full-scale CCS facility on a **waste-to-energy** plant. The Klemetsrud project is partly financed by the Norwegian Government as part of the Norwegian full-scale CCS value chain, Longship. When realized the project will capture 400,000 tonnes of CO_2 per year.

The Klemetsrud project is replicable to around 500 existing plants in Europe. If Europe is to reach its landfill targets and recycle targets, the EU will need around 100 additional waste-to-energy plants at the size of Klemetsrud just to be able to move waste from landfills to incineration.

An important aspect of waste-to-energy with CCS is the fact that around 50% of the waste is of biogenic origin, which makes it a BECCS facility. Hence, the technology can contribute to large scale carbon removals. The potential is huge. ETH Zurich estimates that the waste-to-energy with CCS in Europe has a potential to remove 36 mill tonnes/yr of CO_2.

Business models: There are good opportunities for different revenue streams. With these plants, carbon neutral waste handling services can be offered to a premium price to companies and municipalities looking at reducing their indirect emissions. And for the carbon negative part, carbon removal certificates can be sold on the voluntary carbon market, or at state-led reversed auctions as Sweden is planning. Both Stockholm Exergi and Hafslund Oslo Celsio experience a lot of interest and potential buyers are contacting them at the moment.

- **Direct Air Capture (DAC)**, the most expensive and energy intensive CDR solution, can enable large-scale carbon removal from the atmosphere without land-use trade-offs at the same scale as BECCS/afforestation. Areas with abundant natural CO_2 storage capacity and cheap access to energy will be suitable for DAC. The concept has received increased attention globally in the carbon planning and policy discussion. Global Change Assessment Model (GCAM) results by PNNL shows that more DAC is scaling up in the mid-century when biomass use gets more restricted for some of the social and sustainability reasons. The analysis indicate that DAC technologies are expected to capture more than 85 mill tonnes of CO_2 per year in 2030 increasing to ~980 mill tonnes of CO_2 per year in 2050. The first large-scale DAC plant having a CO_2 sequestration and storage capacity of up to 1 mill tonne per annum is in advanced development in the US.

  Companies such as Microsoft have pledges to become a negative emission company and to do so they will have to place a premium on the permanence that DAC offers. However, reaching a billion tonne negative emissions per year from DAC is going to require strong public and financial support in the regions it is going to be deployed. Not just for the DAC plants themselves but for all infrastructure surrounding. Transportation, disposal infrastructure including disposal wells are critical parts in this picture. All of this is dependent on the broader technical and social viability of CCS.

EU as all other regions, will require carbon removals to reach carbon neutrality. With respect to the captured CO_2, the EU alone will need geological storage capacity of 300 mill tonnes CO_2 annually by 2050 to permanently store the CO_2 captured from avoidance and removals. Currently the **geological storage** capacity is zero. By 2030, the 30 projects under preparation can deliver about 50 mill tonnes of CO_2 storage annually. Reaching climate neutrality in Europe will need at least six times more CO_2 to be stored per year by 2050.

Another important aspect for EU on the journey to climate neutrality is to establish **an open-access cross-border CO_2 infrastructure.** This will assure that CO_2 can move freely in the EU. It is important that this system is open and transparent and founded on fair competition. EU also plan to have a legislative proposal on a **regulatory framework for the certification of carbon removals** by 4Q2022.

Regarding negative emissions, EU does not foresee negative emissions to be included in the EU ETS system in the shorter term. Before 2030, negative emissions will have to lean on the voluntary market.

Well-functioning **carbon markets** are key measures to obtain climate neutrality and the demand for carbon offsetting is growing. The current voluntary carbon market is small but is expected to grow 15–30% per annum and to reach USD 50–100bn per year by 2030. The demand for high-quality credits is outstripping supply and there is a big shortage of high-quality credits. Investors are looking for high-quality cost-effective measures and carbon removals will play an increasing role as these markets develop. The voluntary markets, as such, play a role in bringing finance to emission reduction and carbon removals and a well-functioning market is part of the solution for meeting the climate ambitions.

> What we are basically looking at is how to develop a CDR industry probably using both nature-based solutions and industrial techniques like the fossil fuels industry and establishing social practices in an economy at record pace. So, it is a fundamental challenge.
> — J. Røttereng, Enova SF

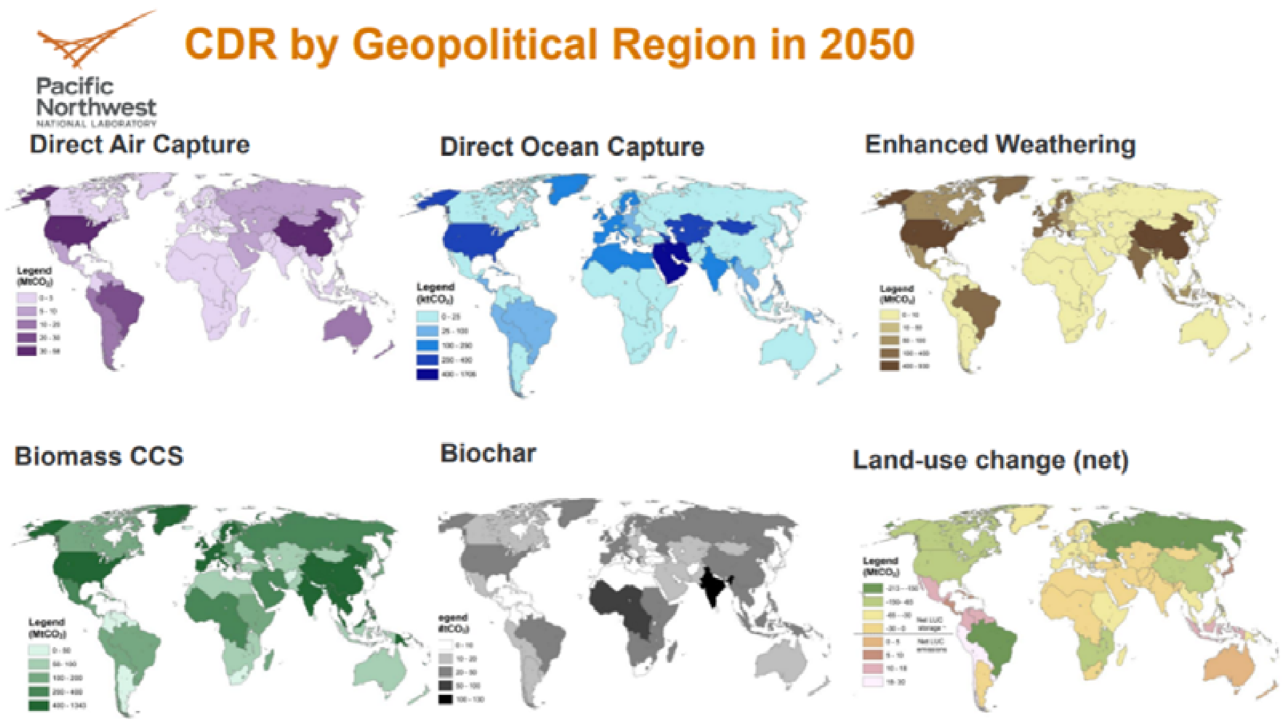

Figure 1: *Negative co_2 emissions by CDR method and GCAM region in 2050. Greenland is plotted as part of the EU-15. Mongolia is considered as part of GCAM Central Asia region but does not have meaningful data on direct ocean capture potential (Source: PNNL)*

In this respect, a lot has moved in the right direction over the last year, and new questions are being raised.

- **CDR increasingly becomes mainstream mitigation policy.** A recent development is that national mitigation targets focus on «net zero» by 2050. Consequently, governments increasingly emphasize CDR based methods as a part of the overall portfolio of options;

- **Investors' recent interest in CDR is also new** and sees a strong demand, as exemplified by Frontier's (approx.) USD 1bn initiative: https://frontierclimate.com/;

- **New regulatory push to include CDR at the EU level climate policy is also new** and a milestone that perhaps could not be envisaged three years ago;

- **Despite increased interest and urgency, we still face significant knowledge gaps on how to deploy CDR at the required scale on acceptable terms.** Overcoming knowledge barriers requires input from all disciplines e.g., natural sciences, biology, technology, public policy and economics, business development, law and more; and

- **As it will take time to eliminate emissions from fossil fuels, stimulating the voluntary market with high quality CDR projects will be of utmost importance** for the companies to compensate their emissions along the way. The voluntary market must avoid greenwashing by offering highest quality credits and with that ensure high-quality offsets. A high-quality project is additional, verified, provides co-benefits, and limits leakage. Access to quality credits is one of the biggest challenges for the voluntary market today. We must create standards and make sure that the projects stand up to scrutiny.

However, given the limited time available to scale up CDR (and other mitigation), should we allow a higher acceptance for implementation risk (trial and error) or would that be contra productive?

CONTENTS

INTRODUCTION

Negative emissions and carbon dioxide removal (CDR) at scale is required to offset hard to reduce emission streams and remove historic emissions from the atmosphere. The more we emit cumulative before we reach net zero, the more we must take out from the atmosphere to meet the climate ambitions.

This report summarizes highlights from the workshop on Negative Emissions and Carbon Dioxide Removal (CDR) including Ocean Scenarios held 1 April during the NTNU Energy Transition Week 2022.

The purpose of the workshop was to seek updated insight and look closer at the drivers, uncertainties, and deployment potentials. The workshop concentrated around three CDR solutions that all can make a difference at scale: **Seaweed farming, BioEnergy with Carbon Capture and Storage (BECCS)** and **Direct Air Capture (DAC)**. The three selected solutions represent the span of CDR technologies ranging from pure nature-based solutions, through hybrid nature-based/engineered solutions to pure engineered solutions. By including seaweed farming it also highlights the ocean's significant sink potential. Included in the workshop were also a mini-dive into the ocean CDR regulations and legal framework, the latest policy developments and regulatory moves in EU with respect to CDR, and a look at the carbon market as a financial muscle to the must come CDR industry.

The workshop was the second in a series on the topic.

Note: This report should not be used as scientific facts and conclusion, but rather as a summary of important issues and aspects discussed at the workshop.

You can read the previous report, «Negative Emissions and Carbon Dioxide Removal (CDR) - Technologies, international policy environment and business models» from 2021 by scanning this QR-code.

THE CLOSE LINK BETWEEN NATURE AND CLIMATE

Nature and climate are closely linked, and loss of nature has tremendous impact on climate change. Understanding these links help making better decisions with respect to negative emissions and CDR.

This section gives a short introduction to the neat interlinks between atmosphere, vegetation, soil and ocean and the feedback cycle taking place and enforcing the climate risk.

First some key processes and systems:

- **The photosynthesis:** The process by which plants use sunlight, water, and CO_2 to create oxygen and energy in the form of sugar. The world's most important reaction? About half of the human emissions are absorbed by sinks, primarily driven by the photosynthesis, fixed by primary producers at land and in the ocean. And it happens in our timescale;
- **The carbon cycle:** The «nature itself» rules foster a delicate interlinked system (Figure 2). The sinks' efficiencies vary with changing environment;
- **Terrestrial systems:** The boreal forest on the Northern hemisphere is the largest terrestrial carbon-storage (703 Gt) together with the tundra (1400 Gt) on the planet. It stores six times more carbon than the temperate forest (121 Gt) and twice as much as the tropical forests (375 Gt) (Hance J., 2009). If the sequestration is weakened or in the worst case reversed, it will have tremendous impact, not only on the atmosphere, but also on the ocean; and
- **Aquatic systems:** Water can be viewed as the hub at landscape scale. The different catchments have widely different properties. The catchment is affected by climate forcing, land-use and atmospheric deposition. Water integrates and responds to terrestrial changes, and this will also affect downstream coastal waters.

It is important to link terrestrial processes to aquatic processes and then the impact on carbon fixation in the marine systems, especially in the coastal parts. Key aspects here are:

- Transport of particles, dissolved organic carbon (DOC) containments as well as key elements (N, P, Si, Fe, and Ca);
- Temperature, precipitation, and permafrost thaw, all drivers of emissions and fluxes; and
- Export also of inorganic carbon is important for long term marine buffering.

A lake is not a closed entity, and does not primarily mirror the sky, but mirrors the catchment properties. Dissolved organic carbon (DOC) from the soil enters the lakes and darkens it. DOC has a huge impact on the light penetration and hence the lake's catchment properties and primary production. Even crystal-clear lakes have a significant trapping of light caused by DOC. The DOC effect gives substantial feedback to climate CO_2 and methane (Thrane J-E. et.al., 2014).

As the ocean warms up and becomes more acidic, it will sequester less CO_2 which again is bad for the primary production in the oceans and for the ecosystem productivity as such. On the other hand, combating acidification can lead to unwanted browning of water.

In **the axis «vegetation – climate interactions»** both positive and negative feedbacks are found. Greening of land increases the CO_2 sink on land, however, also increases DOC and this increases the loading of coloured water which again will generate more CO_2 and less CO_2 uptake. It also results in reduced albedo (albedo: the portion of incident light or radiation that is reflected by a surface) and hence has an escalating warming effect. Tundra melting as a side effect of warming increases the loading of DOC as well as giving significant release of methane and CO_2 to the atmosphere. This again has a large impact on the aquatic system.

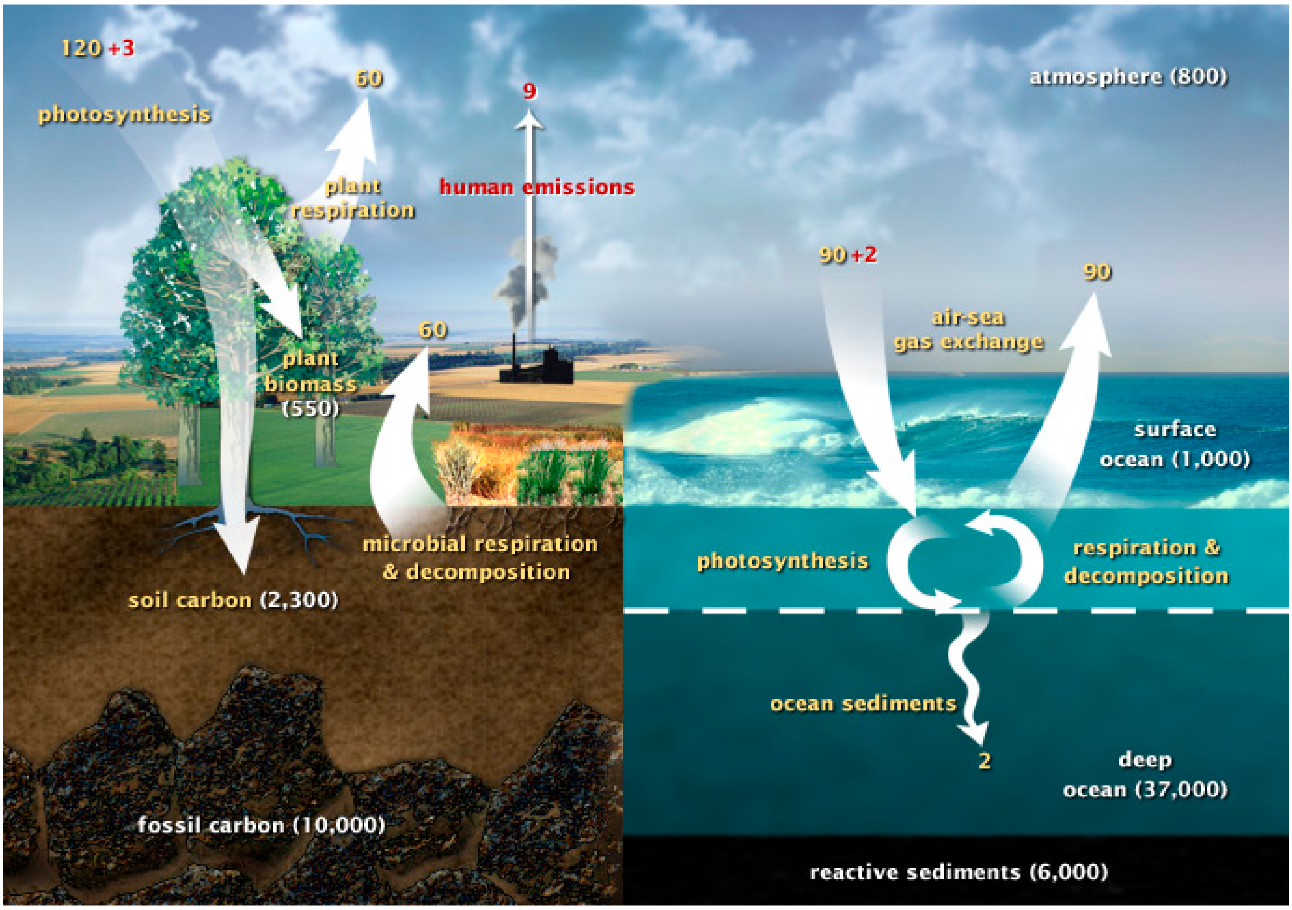

Figure 2: *This diagram of the fast carbon cycle shows the movement of carbon between land, atmosphere, and oceans. Yellow numbers are natural fluxes, and red are human contributions in gigatons of carbon per year. White numbers indicate stored carbon (Source: Riebeek, H et al., 2011)*

Some significant links in **the axis «river to sea»** are the greening in land which promotes browner water which again affects lakes and coastal primary production, carbon sequestration and methane emissions and the coastal blooming and spawning.

The linking of land to optical properties of the water will e.g., also affect the carbon sequestration of the seaweed forests and the deeper waters' optical properties.

The close link between ecosystem properties and the climate risk is this feedback cycle that is now occurring and might be strengthened by temperature rising. This is a strong argument for preserving a healthy ecosystem and restoring land.

And there is still a large unexplored value in the open ocean for carbon sequestration.

SEAWEED FARMING

For simplicity, there are five ocean CDR technologies: i iron, nitrogen, and phosphorous fertilization, ii artificial upwelling and downwelling, iii seaweed cultivation, iv electrochemical ocean CDR approaches and v ocean alkalinity enhancement.

This brief concentrates on seaweed farming as being the most promising ocean CDR solution.

Seaweed farming is a significant industry at global scale with a production of 30 mill tonnes/yr. The current production is primarily in the Southeast Asia and China and mainly for food and feed. Also, the western part of the world has started to look at it. In Norway, seaweed farming has just started and there are about 20 farmers as of now, producing a few hundred tonnes per 2021.

Seaweed farming does not compete with arable land, it uses the photosynthesis (it's for free) and the ocean (it's huge) for carbon removal. Neither does it need fresh water, soil nor any pesticides, nor any fertilizers. And seaweed is a great feedstock for a lot of products as food, feed, medicine, materials, biofuel, crop nutrition, ocean restoration, to mention some. Hence, there are many opportunities to unlock new seaweed value chains.

In 2019, UN's High-Level Panel published the report *The Ocean as a Solution to Climate Change* where they among other issues describe coastal and marine ecosystems and how they can be better used for climate purposes. They highlighted seaweed farming as one possible solution to be further investigated and tested and elaborated. It has a huge potential for CO_2 uptake through biomass growth, up to 0.3 $GtCO_2eq$/yr globally.

Since then, research and several reports have been published highlighting the potential of seaweed under titles as *Seaweed revolution – A manifesto for a sustainable future* (UN Global Compact, 2020) and *Hidden champion of the ocean – Seaweed as a growth engine for a sustainable European future* (Seaweed for Europe, 2020).

Especially cultivation of fast growing, large kelp species like *Saccharina latissima* provides large scale biomass production with annual harvesting.

Off the coast of Norway, the estimated production potential is 20.000 tonnes seaweed (e.g., kelp) pr km² per year which again can capture 2500–3000 tonnes CO_2 pr km². Comparing this to Norway's total CO_2 release (49.3 mill tonnes CO_2eq in 2020), an area of 20.000 km² of seaweed farms can offset this whole amount (SINTEF Ocean) (Figure 3). Norway has good natural conditions for such farms along most of the coast and especially offshore, where the temperature and nutrient supply is more stable than inshore.

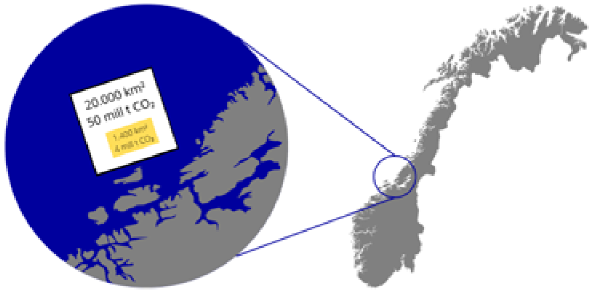

Figure 3: *Case Norway – seaweed farming comparison to Norway's total CO2eq emission (Source: SINTEF rapport 'Nye muligheter for verdiskaping i Norge)*

If the CO_2 is stored permanently, seaweed farming can become a CDR solution at scale. Below are described three options (Figure 4):

- **Passive CO_2 storage from Offshore seaweed farming:** A fraction (10–15%) of the kelp carbon is released during the farming due to tissue erosion and dissolved carbon from the seaweed. A fraction (uncertain how much) will sink down and deposit at the seabed. If deep enough, the sediments will not mix up into the atmosphere again, hence the deposited CO_2 becomes permanently stored and kept out of the short carbon cycle;

- **Active CO_2 storage from Offshore seaweed farming:** Active harvesting and sinking of kelp biomass for deposition below 1000 m depth. From these depths it will not mix back into the atmosphere. Both the passive and active CO_2 storage on the seabed sediments from offshore seaweed farming may be controversial due to possible negative impact on the sea floor ecosystem and need to be tested and understood better before initiated at a large scale; and

- **Active CO_2 storage from Coastal or Offshore seaweed farming:** The harvested biomass can, in theory, be stored permanently on land depending on use: It could for example be feed stock to BECCS-plants and generate negative emissions or be converted to biochar and stored permanently in the soil. A potential barrier for seaweed as feedstock to BECCS-plants is the high water content and required energy-consumption. The energy potential in seaweed and challenges to

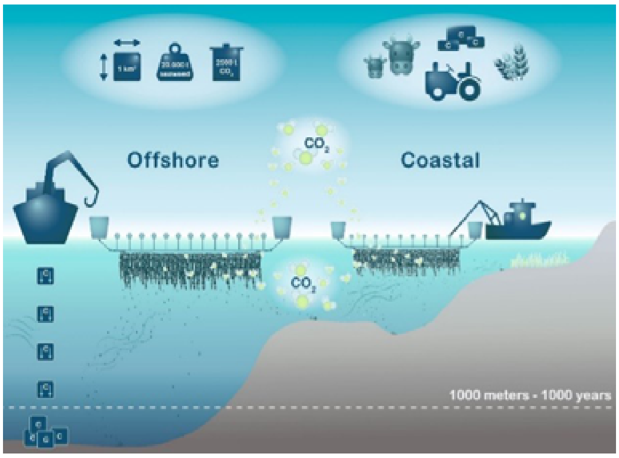

Figure 4: *Offshore and coastal seaweed farming and pathways that make it into CDR solutions (Illustration: SINTEF Ocean)*

be addressed will be studied in the research project «NCS C+» headed by SINTEF Energy Research. The production potential for kelp biochar is estimated to 600–800 tonnes per km² sea surface. If the biochar is produced at high temperatures above 400ºC and stored in the soil it is recognized as a CDR technology. Biochar mixed into the soil does not only remove CO_2 from the atmosphere. It also increases the pH of the soil, increases the water holder capacity of the soil which prevents the soil from drying out, and it works as a vector for organic fertilizer.

Current seaweed production methods are labour intensive and high production costs indicate utilization of the biomass in more valuable end products like food and cosmetics than for CDR solutions. A thorough upscaling is needed along the whole value chain to reduce the costs and for this production methods that are more automized and mechanized must be developed and technology transfer from the offshore industries to biomass production should be looked for. Work on up-scaling of production with less labour-intensive technologies has just started, e.g., in the joint industry project «Seaweed Carbon Solutions» coordinated by SINTEF Ocean. Since dried biomass is preferred both in BECCS and biochar production an integration with waste heat generating industries, preferably coastal ones, with CCS established, would ensure a more complete exploitation of the resources in new CDR value chains.

As of now there are no specific international rules for the different ocean CDR technologies, neither are there international instruments that deal with CDR, nor any specific guidelines on how to report negative emissions for ocean CDR. Each ocean CDR technology have specific legal challenges.

There are, however, a set of rules at national and international levels that will apply. The interest for them is different according to the jurisdiction. Appendix A gives a short overview of the current legal frameworks for ocean CDR offshore Norway (an EEA country) with respect to jurisdiction.

If to succeed with ocean CDR, there will be a need to push for signals to proceed. Without that push, enabling an adequate legal framework will not proceed very fast. The research project «NCS C+» will address some legal perspectives, however, not more than what is being pushed for.

Seaweed farming as a CDR solution at scale can happen fast and ensuring a permanent storage pathway if we want to do this. It boils down to will, funding, and regulatory moves and establishing a legal framework.

Photo: SINTEF OCEAN

BIOENERGY WITH CARBON CAPTURE AND STORAGE, BECCS

A BECCS plant in the shape of a waste-to-energy plant with CCS is a low hanging fruit: It handles waste, produces energy, cuts emissions, and it can create negative emissions.

However, BECCS at scale can also come in conflicts with e.g., land-use, water usage and biodiversity if the land and/or the feedstock could be used for other purposes.

The two examples below give a snapshot into the first large-scale plants in Europe, both due to start production in the mid-twenties and both do not conflict with the issues mentioned above.

Example: Sweden and Stockholm Exergi

By 2045, Sweden is to have zero net emissions of greenhouse gases into the atmosphere and will thereafter become climate positive.

Sweden has an active and large forestry and forest industry and has the potential to produce more than 30 mill tonnes of CO_2 negative emissions annually. The country will need 3–10 mill tonnes CO_2 negative emissions annually to reach net zero. Should negative emissions become larger it can be exported and help others to offset their hard to abate emission streams. The key measure on this journey is BECCS where Stockholm Exergi (Stockholm's energy company), will be first out with its planned large-scale negative emission plant due for production in 2025. The project is supported by the EU Innovation Fund with EUR 180 mill.

The plant will generate negative emissions from a biomass fed combined heat and power plant. The fuel is bark and treetops, hence pure leftovers, and residues from the forest industry. The concept basically combines photosynthesis with carbon capture and permanent storage in external storage facilities such as the Northern Lights project in Norway. It requires no outtake of biomass.

The process is thermodynamical like a heat pump process where it extracts heat from the condensed water from the CO_2 flue gas and turns it into district heating. This means that in the end the plant has more output combined than the heat content in the fuel supply to the powerplant. The 2.3 TWh forest residues used, generates 2.2 TWh district heating, 250 GWh electricity and about 800,000 tonnes of negative emissions (Figure 5).

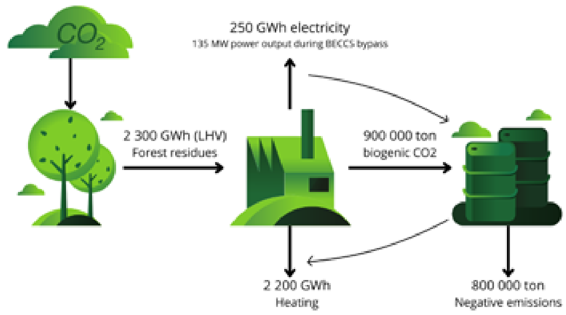

Figure 5: *The energy streams of the Stockholm Exergi's BECCS plant*

The negative emissions created can be part of an offset market to be tapped into for those with hard to abate emission streams, hence contribute to Sweden's and Swedish and international companies' goals of achieving net zero emissions. The cost of negative emissions from a BECCS plant like the Stockholm Exergi's is 100–200 USD/tonne CO_2.

The fundamental idea of the combined heat and power in this BECCS plant is to use residue only. Sweden has the potential to take out 10–30 TWh more without conflicting with primary use.

Example: Waste-to-energy with CCS and the Klemetsrud plant in Oslo

Hafslund Oslo Celsio is planning to build a full-scale CCS facility on their Klemetsrud waste-to-energy plant. The plan is to start the construction work in July 2022, and when ready in 2026, it will be the world's first of its kind.

Oslo, the capital of Norway, has set the goal of reducing its emissions by 95% within 2030. While waste-to-energy can reduce emissions related to waste handling with up to 75% compared to landfilling, there are still large emissions that need to be addressed. Currently, the Hafslund Oslo Celsio's Klemetsrud plant accounts for 17% of Oslo's emissions, making the city dependent on Celsio's CCS project to reach its climate ambitions.

The full-scale CCS facility when realised will capture 400,000 tonnes of CO_2 per year. This corresponds to the emissions from around 200,000 fossil cars. The project is partly financed by the Norwegian Government as part of the Norwegian full-scale CCS value chain, Longship.

Deployment potential: The Klemetsrud waste-to-energy CCS project is replicable to around 500 existing plants in Europe. If Europe is to reach its landfill targets and recycle targets, the EU will need around 100 additional waste-to-energy plants at the size of Klemetsrud just to be able to move waste from landfills to incineration.

An important aspect of waste-to-energy with CCS is the fact that around 50% of the waste is of biogenic origin, which makes it a BECCS facility. Hence, the technology can contribute to large scale carbon removals. The potential is huge. ETH Zurich estimates that the waste to energy with CCS in Europe has a potential to remove 36 mill tonnes/yr of CO_2.

Business models: There are good opportunities for different revenue streams. With these plants, carbon neutral waste handling services can be offered to a premium price to companies and municipalities looking at reducing their indirect emissions. And for the carbon negative part, carbon removal certificates can be sold on the voluntary carbon market, or at state-led reversed auctions as Sweden is planning. Both Stockholm Exergi and Hafslund Oslo Celsio experience a lot of interest and potential buyers are contacting them at the moment.

Photo: Einar Aslaksen, Hafslund Oslo Celsio

DIRECT AIR CAPTURE, DAC

DAC can enable large-scale carbon removal from the atmosphere without land-use trade-offs at the same scale as BECCS/afforestation. The concept has received increased attention globally in the carbon planning and policy discussion.

DAC is very expensive (above 1000 USD/tonne CO_2 captured), and the most energy-intensive CDR technology. Despite this, the concept is gaining interest from private companies, governments, and financiers.

So, what is DAC?

DAC is a family of processes that use either solid or liquid absorbents to uptake CO_2 from the atmosphere and create a concentrated stream of CO_2 by using energy usually in the form of high or above 900ºC heat or low temperature heat around 100ºC to essentially kick the CO_2 off the capture medium.

There are at least three DAC start-up companies that have demonstrated at-scale plants. Several of these have got investments from partnerships with other companies seeking to reduce or offset their carbon emissions.

The Canadian company Carbon Engineering uses the high temperature process, whilst the Swiss company Climeworks and the US company Global Thermostat is working on the low temperature amine-based process.

The US company Heirloom is working on a DAC process where the chemistry is based on the mineralization reaction that normally influences climate on millennial timescales. It blurs the line between the two CDR processes, but until now little is publicly known about the technical processes and workings of their technology.

Early deployment helped by CO_2 utilization applications (e.g., e-fuels, enhanced oil recovery) and voluntary corporate actions (e.g., Microsoft) will continue to be important to start unlocking the potential for DAC and bring the costs down.

Areas with abundant natural CO_2 storage capacity and cheap access to energy will be suitable for DAC.

Global Change Assessment Model (GCAM) results by PNNL shows that more DAC is scaling up in the mid-century when biomass use gets more restricted for some of the social and sustainability reasons (Figure 6). The analysis indicate that DAC technologies are expected to capture more than 85 mill tonnes of CO_2 per year in 2030 increasing to ~980 mill tonnes of CO_2 per year in 2050. Under such a scenario, an average of 32 large-scale DAC plants of ~1 mill tonnes per year of DAC capacity each, must be built annually until 2050. The modelling work also indicates that the amount of CDR required depends on technology and level of behavioural change.

The first large-scale DAC plant having a CO_2 sequestration and storage capacity of up to 1 mill tonnes per annum is in advanced development in the US. This is 1PointFive's planned facility with anticipated construction start in 2022 in the Permian Basin using Carbon Engineering's industrial scale DAC solution (https://carbonengineering.com/, 2022).

How to get to billions of tonnes CO_2 scale?

Reaching the scales of billions of tonnes negative emissions per year from DAC is going to require strong public and financial support in the regions it is going to be deployed. Not just for the DAC plants themselves but for all infrastructure surrounding. Transportation and disposal infrastructure including disposal wells are critical parts in this picture. All of this is dependent on the broader technical and social viability of CCS.

Scaling up DAC requires society-wide mobilization to decarbonize. Most likely it must be decided that it is not allowed to emit greenhouse gases (GHG) into the atmosphere, hence treat it as a parallel to waste water treatment. Near term policy support for DAC R&D and deployment are essential to minimize long-term risks. And DAC must not substitute mitigation. Reducing emissions will always be the top priority.

And hopefully, this will be accompanied by a steep decline in costs of DAC.

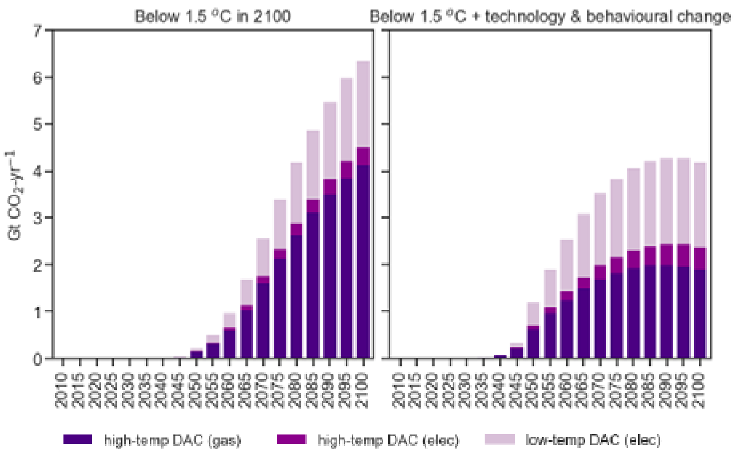

Figure 6: *Projected global Direct Air Carbon Capture and Storage (DACCS) deployment by technology (Source: PNNL)*

In March 2022, the three-year Norwegian research project *NCS C+ – The Norwegian Continental Shelf: A Driver for Climate-Positive Norway* was launched. «NCS C+» aims to develop four climate-positive technologies that will remove large volumes of carbon dioxide and methane from the atmosphere. These four technologies are: i Converting algae and/or waste bio-resources into hydrogen and/or heat with CCS, ii Removing CO_2 from seawater, iii Removing CO_2 from the air (DAC), and iv) Removing methane from the air.

In doing so, «NCS C+» will leverage the Norwegian Continental Shelf's assets to support the safe and cost-efficient implementation of these CO_2 removal technologies, as well as their transport and storage.

The scientific results of «NCS C+» will potentially contribute to increasing the momentum in Norway and Europe for carbon capture and storage (CCS) and provide the necessary context for climate-positive solutions.

«NCS C+» brings together research actors in a consortium and is coordinated by SINTEF Energy Research.

Photo: Ørjan Ellingvag, Alamy Stock Photo

POLICY DEVELOPMENT AND REGULATORY MOVES

With respect to CDR policy development, a lot has moved in the right direction over the last year and CDR increasingly becomes more mainstream mitigation policy.

Below is a closer look at the latest development in EU relevant for CDR.

To achieve climate neutrality at the latest by 2050 and negative emissions thereafter, the EU needs to **increase carbon removals and establish sustainable carbon cycles**. This means in short:

- Drastically reduce the use of fossil carbon: i.e., increase efficiency and implement «fit-for-55»;
- Recycle and reuse carbon: i.e., replace fossil carbon by new sources of carbon; and
- Increase carbon removals: i.e., utilize CDR to remove hard to abate emission streams from sectors as industry, transport, and agriculture.

The EU will, in addition to decarbonizing its energy system, also need to rethink its sourcing of carbon as feedstock for industrial processes. Key here will be to **create an internal market for the sustainable capture, use and storage of CO_2** with the purpose to i replace energy-intensive materials (e.g., cement and steel) with bio-based materials which store carbon, ii transform CO_2 from a waste product to a resource, and use it to produce materials, chemicals and fuels, and iii remove carbon from the atmosphere.

By 2050 EU will need to industrially capture 300–550 mill tonnes CO_2/yr. Important key milestones and action plan set to get this moving are:

- **By 2028** all CO_2 captured, transported, used, and stored should be reported and accounted and
- **By 2030** 20% of carbon used in plastics and chemicals are non-fossil and 5 mill tonnes of industrial carbon removals.
- **The action plan** to reach the above short-term goals includes i methodology for carbon storage in construction, ii EU bioeconomy land-use assessment, iii support via the Innovation Fund (IF), iv Horizon Europe calls on CCS, v study on CO_2 transport network, vi update guidance for CCS directive and vii annual CCS forum.

In EU, the current **geological storage capacity for CO_2** is zero. The capacity must increase to 300 mill tonnes CO_2/yr by 2050 if to reach the climate goals. The first round of Innovation Fund (IF) project proposals indicated a capability of 3.5 mill tonnes CO_2 /yr geological storage, but there are many more projects in preparation. By 2030, the 30 projects under preparation can deliver about 50 mill tonnes CO_2 storage. Reaching climate neutrality in Europe will need at least six times more CO_2 to be stored per year by 2050.

Another important aspect on the journey is to establish an **open-access cross-border CO_2 infrastructure.** For EU, this means i connecting CO_2 sources with sinks, including sites and production sites using CO_2 as feedstock, ii drive down costs through competition in an open EU market and iii establish CCUS hubs to leverage economies of scale across EU. This will assure that CO_2 can move freely in the EU. It is important that this system is open and transparent and founded on fair competition.

A key stimulation mean will be the **Innovation Fund (IF) for demonstration of low-carbon technologies**. IF is one of the world's largest funding programmes and first of its kind. The first large-scale call resulted in financial support to seven projects that total EUR 1bn. Four of these have CCS aspects including the support to the Stockholm Exergi's BECCS plant. The second large-scale call period closed in March 2022 are now being evaluated. The call received 138 project applications totalling EUR 12.1 bn. The plan is to grant EUR 1.5 bn in total to the winning projects. The third large-scale call is expected to take place soon thereafter.

EU also plan for its first **annual CCUS Forum** in October 2022. The following three workgroups are established to prepare the input to this first forum: **i** a workgroup on CO_2 infrastructure, **ii** a workgroup on industrial partnership and **iii** a workgroup to prepare a draft CCUS vision paper on the strategy for the future for CCUS.

The next step developing this year is to have a legislative proposal on **a regulatory framework for the certification of carbon removals by 4Q2022**. The framework will set robust certification requirements on **i** measurement and monitoring, **ii** additionality which is very important when it comes to generating credits, **iii** duration of liability and **iv** environmental safeguards and co-benefits. It will also include a framework for effective, cost-efficient, and transparent implementation and finally also have rules for carbon farming and industrial carbon removal projects.

Regarding negative emissions, EU does not foresee negative emissions to be included in the EU ETS system in the shorter term. Before 2030, negative emissions will have to lean on the voluntary market.

ENOVA SF

Enova SF is the Norwegian Government's funding agency for climate technology. The entity is fully owned by the Ministry of Climate and Environment and supports technology development from the late stage of technology development and early market introduction in all sectors of the economy. It has an annual budget of around EUR 400 mill (or about NOK 4bn) to support Norwegian activities.

Enova acknowledge the crucial importance of carbon capture technologies and have **recently supported the piloting of novel captures technologies** that may also contribute to negative emissions. Enova's focus in this area is currently on supporting technology development to reduce the cost of capturing carbon.

THE CARBON MARKET

Well-functioning carbon markets are key measures to obtain climate neutrality. The demand for carbon offsetting is growing. Investors are looking for high-quality cost-effective measures and carbon removals will play an increasing role as these markets develop.

This section takes a closer look at today's market and what is required to make it well-functioning.

Today there are three carbon pricing mechanisms:

- **Emission Trading Schemes (ETS):** Regulated entities are given rights to emit. They are subject to an emission cap and can freely buy and sell carbon allowance. Some schemes may also allow some offsets if deemed compliant;
- **Carbon tax:** Fee on the carbon content of fossil fuels; and
- **Voluntary markets:** Companies buy carbon credits («carbon offsets») and retire them to «offset» emissions and make claims.

The ETS and carbon tax deal with the emissions in the companies' own supply chain. The voluntary markets, on the other hand, allows companies to take measures outside their supply chain and choose to buy credits to offset emissions and make claims. The voluntary markets, as such, play a role in bringing finance to emission reduction and removals and a well-functioning market is part of the solution for meeting the climate ambitions.

The current voluntary carbon market is small but is expected to grow 15–30% per annum and to reach 50–100bn USD/yr by 2030. The demand for high-quality credits is outstripping supply and there is a big shortage of high-quality credits.

The nature-based solutions clearly outperform engineered solutions when it comes to costs with low-cost reforestation, aforestation and agro-forestry being the cheapest and DACCS the most expensive solution. For these reasons, companies in the market are normally looking towards natural sinks first before they move over to CCS and BECCS and eventually to DAC.

The voluntary market must avoid greenwashing by offering highest quality credits and with that ensure high-quality offsets. A high-quality project is additional, verified, provides co-benefits, and limits leakage.

With **additional** means that the projects that are financed would not have been financed without the purchase of the credits.

A **verified** project applies an approved methodology to ensure net greenhouse gas (GHG) emissions reduction/removals have taken place and are measurable. It uses conservative assumptions, values and procedures and the projects are verified by a recognized third party. It must prevent double counting, be transparent and permanent.

There are **other benefits** than carbon removal that can be achieved through offsetting. These must also be included when evaluating a project's quality. A major concern with increasing CO_2 removal demand, especially for biomass-based CDR options, is negative side-effects on other sustainability goals, foremost nature biodiversity and food production.

Adequately **leakage prevention** ensures that efforts to reduce emissions in one place do not lead to corresponding increases in emissions elsewhere.

Extending the carbon market perspective?

If tropical tree cover loss and peat drainage was a country, it would have been the third biggest emitter in the world. This problem cannot be ignored. The voluntary carbon market has a role to play here as bringing finance to what is an economic problem.

Deforestation and peatland drainage is a result of that alternative land-use is being more economically beneficial for communities. So, finding ways to channel finance to those communities to provide incentives to stop this is a major task and is also going to make a major contribution to what we are looking for. Avoiding deforestation and peatland drainage has the potential to avoid 4 Gt CO_2 emissions per annum towards the 23 Gt reduction needed by 2030 (Seymor and Busch, 2016). Other important aspects for these natural solutions are that they are urgent, cost effective and deliver co-benefits.

An aggregator can stimulate the market

(Example: South Pole)

There is a need to expand the commercial elements of a carbon market. South Pole receives interest from companies, asking for help on how to meet their emission obligations to become net zero. Transitioning the obligations into demand is one of the challenges right now.

South Pole has teamed up with Mitsubishi Corporation and will in the next few months be launching a market maker for offtake of carbon removals from technical/technological carbon removal projects. It will affectively work as an aggregated purchasing pool offering a fixed price offtake in an advanced market with commitments to companies. This will allow companies to take that pricing generated revenue stream, go to their banks and continue to finance their projects to scale them up. This is all private money coming in to do the offtake of the removals.

Projects targeted are:

- High temperature biochar (>450ºC);
- BECCS projects as well as waste projects;
- Durable product mineralization (enhanced weathering); and
- DAC.

There will be various standards attached to the removals and they will all be high quality removal that is eligible under an accredited standard in the voluntary carbon market. All projects will have to sequester the carbon for at least 100 years to ensure the negativity of the removed CO_2 emissions.

Photo: Unsplash

APPENDIX A: LEGAL FRAMEWORK RELEVANT FOR OCEAN CDR

(Example: Norway)

The international legal framework

- Jurisdiction over Oceans: UN Convention of the Law of the Sea (UNCLOS);
- Legal framework for Ocean CDR, directly / indirectly:
  - — UN Framework Convention on Climate Change
  - — Areas where CDR is not wanted: i UN Convention on Biological Diversity, marine protected areas and ii Regional level: Convention for the Protection of the Marine Environment in the North East Atlantic (OSPAR); and
- Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) and London Protocol.

The EU legal framework

Examples of existing regulations which will be relevant:

- Maritime **Spatial Planning** Directive 2014/89/EU;
- Marine Strategy Framework Directive 2008/56/EC;
- **Water** Framework Directive 2000/60/EC;
- **Alien Species** Regulation 2014/1143/EU;
- Regulation on Aliens Species in Aquaculture 2007/708/EC;
- **Habitats** Directive 92/43/EEC; and
- Regulation on **Organic Production** 2018/848/EU

The national framework for an EEA country (example Norway)

NB: Seaweed may be the most relevant Ocean CDR technology in Norway.

- **Marine planning:** inside and beyond the baseline;
- **Project permitting** (example: seaweed):
  - — Legal qualification of the activity, of the seaweed (ex. Food products), of the facility (floating, bottom-fixed)
  - — Seaweed planting within the baseline: private vs public ownership rights, need for regulatory plan, etc
  - — Seaweed production and cultivation: Aquaculture Act
  - — Seaweed harvesting: Marine Resources Act, Nature Biodiversity Act;
- **Environmental pollution at sea:** Pollution Control Act, Biodiversity Act, Water Regulations;
- **Coexistence of activities at sea,** and procedural consultation rights;
- **Indigenous people rights;** and
- **Accounting** (international and national level) and **reward** (e.g., carbon capture certificates).

The indigenous people rights are often related to fishing rights. Regarding accounting, there is very little, and guidance of a concrete accounting methodology is lacking. Reward is still outstanding.

The legislation reflects the advancement of the technologies and the level of not clear with respect to CDR political signals but also the limitation the legislation put on them. Implementation mitigation measures are lacking, and there are some legal issues that will have to be considered.

A LAST COMMENT

From the IPCC newsroom 4 April 2022 at the launch of the IPCC Working Group III report *Climate Change 2022: Mitigation of climate change*

«The evidence is clear: the time for action is now. We can halve the emissions by 2030.»

«We are at a crossroads. The decisions we make now can secure a liveable future.»

Negative emissions and carbon dioxide removal is now for real on the IPCC menu and hence deemed part of the solution.

So, given the limited time available to scale up CDR (and other mitigation), should we allow a higher acceptance for implementation risk (trial and error) or would that be contra productive?

You can read the Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) scanning this QR-code.

NTNU ENERGY TRANSITION

NTNU