CCS in a biodiversity and land use perspective

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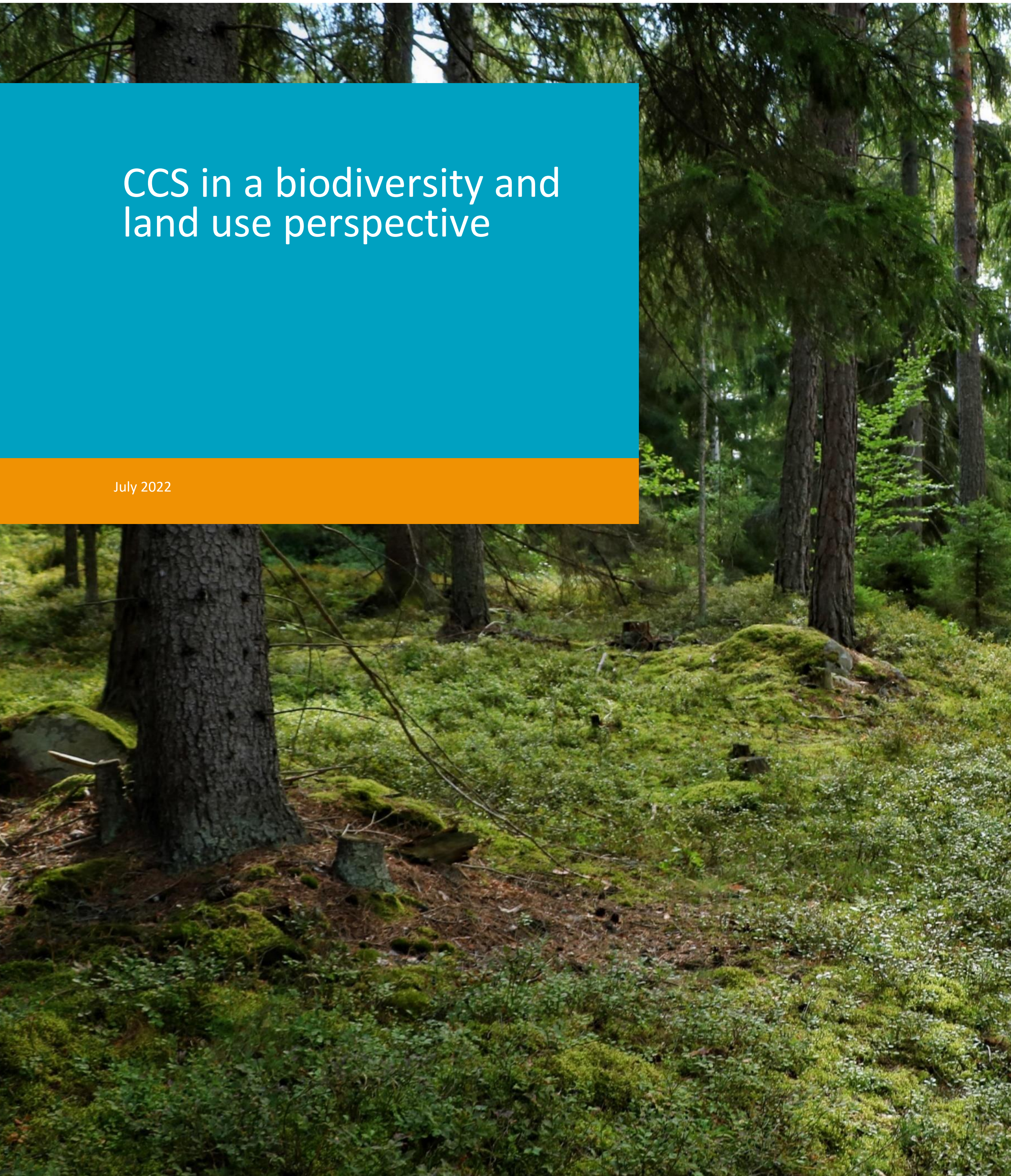

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Executive summary

The European Climate Law states that *"Union-wide greenhouse gas emissions and removals regulated in Union law shall be balanced within the Union at the latest by 2050, thus reducing emissions to net zero by that date, and the Union shall aim to achieve negative emissions thereafter"*.

Climate change is one of the biggest challenges of our times – temperatures are rising, drought and wildfires are starting to occur more frequently, rainfall patterns are shifting, glaciers and snow are melting, and the global mean sea level is rising.

The European Climate Law states that *"solutions that are based on carbon capture and storage (CCS) and carbon capture and use (CCU) technologies can play a role in decarbonisation, especially for the mitigation of process emissions in industry"*.

Twenty EU Member States (MS) have included CCS in their National Energy and Climate Plans (NECP) for the period 2021 – 2030 (CO2GeoNet, 2022). Models indicate that, by 2050, annual investments in carbon capture and storage (CCS) must reach €12.3 billion in Europe to enable 1.5°C warming scenarios (University College London, 2020). All reliable modelling scenarios, including those from the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency, consider the deployment of CCS and carbon dioxide removal (CDR) technologies as critical to reach climate neutrality by 2050 (IEA, 2022).

The IPCC states that:

- "Global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C or 2°C"; and
- "Enabling conditions, such as policy instruments, greater public support and technological innovation, could reduce these barriers." (IPCC, 2022)

There is also a clear recognition of the role of CDR to reach carbon neutrality. Bioenergy with carbon capture and storage (BECCS) could remove cumulatively up to 780 gigatonnes of CO_2 between 2020 and 2100. The IPCC cautions that *"scaling up biomass crop production for the deployment of bioenergy with carbon capture and storage (BECCS) may […] spur additional deforestation"* (IPCC, 2022).

Extinction rates of living species is taking place at a much higher pace than the normal extinction rate. The United Nations Convention to Combat Desertification (UNCCD) explains that land degradation is disrupting rainfall patterns, exacerbating droughts or floods, and worsening climate change. The urgency of protecting biodiversity is reflected by the increased momentum from the latest report of the UN Biodiversity Panel, the joint workshop report between the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and IPCC in 2021, and in the preparations made for the 26th Conference of the Parties (COP26).

The EU biodiversity strategy for 2030 aims to protect at least 30% of the EU's land and sea area by 2030, *"with an emphasis on creating ecological corridors and strict protections for primary and old growth forests"* (European Commission, 2020). Other key targets include planting three billion trees, reducing pollution, fertiliser and pesticide use, reversing pollinator decline, and increasing diverse and organic agricultural management. The mitigation of climate change and the protection of biodiversity are intertwined policy actions.

On the one hand, the uncontrolled use of BECCS could endanger natural carbon storage in forests and establish monocultures of short rotation crops and trees. On the other hand, CCS reduces CO2 emissions to the atmosphere, reduces pollution, and is essential for the EU to reach carbon neutrality by 2050 knowing that global warming from greenhouse gas emissions and associated extreme weather events damage terrestrial and aquatic ecosystems, weaken their resilience and lead to changes in ecosystem structure, shifts of species range, and extinctions (IPCC, 2022).

The impact of carbon capture and storage on land use and biodiversity requires a thorough investigation. This report investigates the biodiversity and land use impacts of CCS to determine actions for future BECCS projects and further research. Biomass with CCS, direct air capture with CCS, and Waste to Energy (WtE) with CCS can support the decarbonisation of sectors of the European economy that are more energy-intensive or where direct electrification will be too costly (ZEP, 2021).

CCS is an essential prerequisite for any facility that uses biomass to qualify as climate negative. Also, biomass requires strict sustainability criteria and adequate forest management practices (ZEP, 2020).

This report makes a series of recommendations to ensure that the best possible option is pursued to achieve carbon neutrality, while avoiding significant harm to biodiversity. These recommendations are the following:

Regarding biomass and raw materials:

- Biomass should not be extracted at a faster rate than the land sink's capacity to regenerate itself.
- Biomass demand should be kept within manageable levels and avoid replacing solutions that have a better net CO_2 abatement or removal potential based on a full life-cycle analysis.
- Biomass use for energy and feedstock purposes should never be used at the expense of food production.
- Biodiversity and other ecosystem sustainability considerations should be a pre-requisite for the production and use of biomass for industrial or energy purposes.
- A cascading principle/merit order should be applied to all biomass use, to ensure judicious application of limited biomass resources. This applies not only to 'fresh' biomass, but also to waste biomass (including municipal waste), for which material recovery and reuse should be prioritised over energy recovery.
- Research should be conducted and funded at the EU level on the potential industrial deployment and impact on biodiversity of seaweed for bioenergy and biomass feedstock.

Regarding CO_2 capture:

- A comprehensive life cycle assessment should systematically be conducted for CCS/BECCS/DACCS projects

including a full set of environmental impact indicators beyond greenhouse gas emissions to assess impacts on land use and biodiversity.
- To minimise the impact on biodiversity and land use, EU funding for CO_2 capture should focus on concentrated flue sources at industrial plants rather than direct air capture.
- Further research should be funded at the EU level to better understand the relative impact of fossil fuel power plants with carbon capture installations on biodiversity compared to fossil fuel power plants with no carbon capture installation.
- CCS on existing biogenic and partially biogenic flue gas sources, such as ethanol fermentation, paper production, and waste-to-energy should be investigated for its potential to deliver carbon dioxide removal with minimal additional impacts to biodiversity and land use.
- For direct air capture, it is necessary to assess the land use and biodiversity implications for both the capture facility and the energy provision.

Regarding CO_2 transport and storage:

- Minimise corridors.
- Use trenchless underground or elevated pipelines to minimise corridor fragmentation.
- Monitor actively and restore disturbed land with native species.
- Facilitate industrial hubs to avoid the dispersion of emitters.
- Encourage the location of new factories from hard-to-abate industries near coastlines to facilitate access to offshore storage.
- Strict measures need to be put in place by operators to prevent CO2 leakage during transport and storage.
- Regarding CO2 injection, proper surveying, construction, and monitoring should be put in place by competent authorities to prevent CO2 leakage.

Regarding Waste-to-Energy activities:

- Waste-to-Energy combined with CCS should be incentivised at EU and national level to fulfil the existing potential.
- Waste-to-Energy facilities combined with CCS should be deployed on a large scale. These facilities should not compete with recycling activities.

The report also highlights that Northern Europe has optimal conditions for the deployment of BECCS plants. The region combines abundant biomass in Sweden and Finland with a very large geological storage capacity in Norway. Denmark also produces a significant share of its electricity via biomass. Finally, the report estimates that the BECCS potential in Waste-to-Energy facilities will amount to approximately 70 million tonnes per year by 2035.

Land use is a key topic as the deployment of CCS may require building on new areas. For an equivalent amount of CO2 captured, the gross land requirement appears to be lower for carbon capture installations at industrial plants than for direct air capture facilities. For the same energy yield, renewable hydrogen and electricity from wind turbines have lower land requirements than biomass, indicating a lower impact on biodiversity. Land use can be a useful approximation to determine future impacts on biodiversity. The land use of carbon capture installations and CO2 transport infrastructure appear to be relatively limited.

1 Introduction

1.1 Background

The European Commission presented the European Green Deal in 2019 as the EU policy response to address climate change and the ongoing biodiversity degradation. The European Green Deal includes a set of policies covering various sectors such as energy, industry, construction, food, transport, and finance. The aim is to reduce greenhouse gas emissions and reach climate neutrality by 2050.

A key part of the European Green Deal is the EU biodiversity strategy for 2030 published in May 2020. This strategy aims to ensure that Europe's biodiversity will be on the path to recovery by 2030 (European Commission, 2020).

The European Commission proposed in July 2021 to increase the EU's target to cut greenhouse gas emission from 40% to 55% compared to 1990 levels. The Fit-for-55 policy package is a set of EU proposed legislation that would bring about this increased ambition. This policy package includes a revision of the regulation on land use, agriculture, and forestry that aims to achieve carbon neutrality in these sectors by 2035, including by setting an *"EU-level target for net removals of greenhouse gases of at least 310 million tonnes of CO_2 equivalent by 2030"*.

The Fit-for-55 package also included a New EU Forest Strategy for 2030 that sets out a plan to plant three billion trees across Europe by 2030.

The proposed strategy refers to the cascading principle, asking governments to *"design their support schemes for the use of biomass for energy in a way that minimises undue distortive effects on the biomass raw material market and harmful impacts on biodiversity"*.

Finally, the Fit-for-55 package includes a proposed revision of the Renewable Energy Directive that would require *"new biomass-based heat and power plants to deliver at least 70% fewer GHG emissions than the fossil fuel alternative"* (European Commission, 2021).

1.2 The importance of CCS

The IPCC report 'Climate Change 2022: Mitigation of Climate Change' states that carbon dioxide removals (CDR) are one of the key pillars to mitigate climate change. The report shows the need for CCS to be deployed at scale globally and describes the role of bioenergy with carbon capture and storage (BECCS). In 1.5°C scenarios, BECCS facilities could remove 30 to 780 gigatonnes of CO_2 through 2100.

The report recognises, however, that *"scaling up biomass crop production for the deployment of bioenergy with carbon capture and storage (BECCS) may displace croplands, and in doing so, threaten food security and spur additional deforestation"*. The report also states that *"the production of biomass crops for BECCS or biochar, when poorly implemented, can have adverse socio-economic and environmental* *impacts, including on biodiversity, food and water security"* (IPCC, 2022). Despite the fact that the deployment of CDR, with and without biomass, is necessary to reach carbon neutrality, both positive and negative impacts are possible:

- CCS itself hinders global warming by helping control atmospheric CO_2 concentrations. It also slows the acidification of oceans, which reduces the severity of global warming and of biodiversity and land use (BLU) impoverishment, which is directly connected to the climate.
- CCS are relatively compact technologies that require less surface compared to other technologies aimed at addressing climate change. However, land use is still required for the transport of CO_2 (*eg,* by pipeline) and for the injection into geologic storage.
- The biomass demand of BECCS, if unchecked or poorly regulated, could end up spoiling natural carbon storage in forests and/or establish monocultures of short rotation crops/trees.
- DACCS requires substantial low-carbon energy that, if provided by wind or solar, can require significant land use.
- Taking carbon capture and utilisation (CCU) into account as well, the potential impacts become broader and more complex. Impacts on land use and biodiversity could increase if the CCU application requires large amounts of materials to be excavated, transported, and distributed. On the other hand, this technology can potentially reduce net impacts by replacing other production methods that may be equally or more harmful.

1.3 This report

ZEP has recognised the importance of biodiversity within the discussion around CCS, CCU, DACCS, and the biomass usage of BECCS. The objectives of this report are:

- to outline the effects of CCS and CCU on biodiversity and land use (BLU) – to give, where possible, order of magnitude, qualitative and quantitative indicators,
- to show the volumes of biomass needed by different industrial sectors for potential BECCS applications and compare it to the potential available biomass and its limitations
- to show the importance of understanding how sustainability will be measured at an overall scale and
- to present examples.

Potential discrepancies between different models from the literature cannot be excluded. The data used serves as an estimation of future impacts.

2 Overview of the various concepts

2.1 Biodiversity

Biodiversity can be defined as *"the variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems. […]"* (Convention on Biological Diversity, 2006).

The IPCC mentions that:

- The continued loss of biodiversity makes ecosystems less resilient to climate change extremes.
- Increased demand for biomass can increase the pressure on forest and conservation areas.
- Safeguarding biodiversity and ecosystems is fundamental to climate resilient development, considering their adaptation and mitigation roles.
- Biodiversity and ecosystem services have limited capacity to adapt to increasing global warming levels, which will make climate resilient development progressively harder to achieve beyond 1.5°C global warming.

2.2 Land use

Human activities influence approximately 70% of the world's ice-free land (UNCCD, 2022). Land is used, among other things, for food production, habitation, recreation, resource extraction, transportation, and waste storage. Currently, 37% of global ice-free land is used for pasture, 22% for forests and 12% for cropland. Only 1% of land is used for infrastructure (IPCC, 2019).

Continued expansion of human land use, as well as climate change, has led to strain on ecosystem services, such as freshwater provision, biodiversity, local cooling and air quality management, and carbon uptake. Since 1960, there has been a 50% increase in dryland drought, a 30% shrinkage in inland wetlands, and a 200% increase of populations in regions experiencing desertification (IPCC, 2020). Changes in land use, in particular deforestation, has resulted in net annual emissions of 5.2 Gt of CO_2 between 2007 and 2016.

The effectiveness of BECCS as a CDR solution strongly depends on several assumptions related to:

- the choice of biomass
- the fate of initial above ground biomass, and
- the fossil-fuel emissions offset in the energy system.

Depending on these parameters, CO_2 removed through BECCS could be offset by losses caused by land-use change (Harper et al., 2018).

2.3 Carbon capture and storage

CCS is defined as *"the capture of CO_2 produced during industrial and energy-related process, its compression and transport to a suitable storage location, where CO_2 is injected in the subsurface and stored safely on a long-term basis"* (IPCC, 2005).

Capture technologies can remove more than 90% of the CO_2 from waste gas streams which would otherwise be emitted to the atmosphere (IEAGHG, 2019). This technology can decarbonise power generation, energy intensive industries, and hydrogen production. For sectors such as iron, steel, cement and chemicals, CO_2 is a by-product of chemical reactions in the manufacturing process and not in combustion. CCS is one of the only solutions to cost effectively address these 'process emissions' and enable these industries to decarbonise.

2.4 Carbon dioxide removals

ZEP has published descriptions of carbon dioxide removal (CDR) (ZEP, 2020 and ZEP, 2021). In short, a CDR process must remove physically CO_2 in a manner intended to be permanent and the quantity removed and permanently stored must be greater than the CO_2 emitted.

Four principles must be taken into account:

1. Carbon dioxide is physically removed from the atmosphere.
2. The removed carbon dioxide is stored out of the atmosphere in a manner intended to be permanent.
3. Upstream and downstream greenhouse gas emissions, associated with the removal and storage process, are comprehensively estimated and included in the emission balance.
4. The total quantity of atmospheric carbon dioxide removed and permanently stored is greater than the total quantity of carbon dioxide equivalent emitted to the atmosphere.

The outcome depends on the sustainability of the processes and of each stage in the supply chain. These two parameters must be assessed by a life-cycle analysis (LCA).

2.4.1 Bioenergy with carbon capture and storage

The IPCC defines bioenergy with carbon capture and storage (BECCS) as *"carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility"* adding that *"depending on the total emissions of the BECCS supply chain, carbon dioxide (CO_2) can be removed from the atmosphere"* (IPCC, 2018).

BECCS enables carbon removal because biomass absorbs CO_2 from the atmosphere through photosynthesis. Following the use of biomass, CO_2 is captured and injected in deep geological formations, which removes it from the natural carbon cycle. This removal creates a net transfer of CO_2 from the atmosphere to permanent storage. If the supply chains are well managed, more CO_2 can be permanently stored than is emitted in the BECCS system, thus resulting in negative emissions.

BECCS plays an increasingly large role in discussions on the transition towards a low-carbon economy. The interactions of all stages of the supply chains for BECCS with biodiversity, land-use, water resources, and food supply should be analysed as well as challenges for LCA and evaluating negative CO_2 emissions.

2.4.1 Direct air carbon dioxide capture and storage

Direct air carbon dioxide capture and storage (DACCS) is the *"chemical process by* which CO_2 *is captured directly from the ambient air, with subsequent storage"* (IPCC, 2018). There are two types of technology available: liquid and solid direct air capture. In liquid systems, air goes through chemical solutions, and the solutions remove the CO_2. Solid direct air capture technology relies on solid filters that chemically bind with CO_2 (IEA, 2021).

3 CO_2 capture: biodiversity and land use implications

CO_2 capture potentially has both positive and negative indirect effects on land use and biodiversity. CO_2 capture can lead to local improvement in air quality due to reduced pollution, as well as reduced greenhouse gas emissions (if coupled with permanent storage), thus reducing negative impacts on ecosystems.

3.1 CO_2 capture at industrial sites

CO_2 capture takes place at existing industrial sites and has limited direct implications in terms of land use. In 2006, the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG) provided an estimation of the surface of CO_2 capture equipment for gas and coal plants ranging from 9,500 to 37,500 square meters (IEAGHG, 2006).

As an example, the 3D project at ArcelorMittal Dunkirk uses a CO_2 post-combustion capture process (Axens, 2022). It captures *"CO_2 contained in blast furnace waste gases using a chemical solvent, extracts the CO_2 from the solvent, and puts it under low pressure". The process allows "the CO_2 to be re-used in furnaces or stored and yields heat"* (ArcelorMittal, 2022). The plant is expected to capture 4,000 tonnes of CO_2 per year (Usine Nouvelle, 2022) and to require 300 square meters. A gross land requirement could be approximated to 0.000075 km2/Mt CO_2, a figure that does not account for the land associated with energy use.

3.2 Direct air carbon dioxide capture

In a recent report describing the current status of direct air capture (DAC), the IEAGHG (2021) states that DAC is today more expensive than many other technical solutions to capture CO_2. Capturing 1 gigatonne (Gt) of CO_2 per year would require up to 23,000 km^2 to include photovoltaic installations that would supply electricity to the plant (IEA, 2022), also creating a land requirement of 23 km2/Mt CO_2.

Since there is no large-scale industrial DAC facility in commercial operation, the land-use estimation should be taken with caution. However, data from the smaller Orca plant provides some preliminary indications.

The Orca facility, currently the largest existing DAC facility, is based in Iceland. It has a surface of 1,700 square metres and a maximal gross removal capacity of 4,000 tonnes of CO_2 per year (La Dépêche, 2021). A gross land requirement could be estimated at 0.04 km2/Mt CO_2. However, this calculation only accounts for the land used by the DAC installation. The IEA measures land requirement associated with liquid and solid DAC is higher, at 1.5 and 0.4 km2/Mt CO_2 respectively. Still, the land requirement of DAC is defined as low compared to other CDR alternatives (IEA, 2022).

The Orca facility should have a limited impact on biodiversity due to its specific conditions. In Iceland, *"only a fourth of the island is vegetated"* and *"vegetation is characterised by low-growing plant species"* (Icelandic Institute of Natural History). Iceland has the lowest average growing stock density in Europe with 10 cubic metres per hectare (European Environmental Agency, 2021).

Direct air capture (DAC) is a technology that is favourably perceived due to its low CO_2 emissions and the circularity of CO_2 emissions. However, CO_2 concentration in ambient air is much lower than in concentrated flue gas sources. For highly efficient decarbonisation, it might be reasonable to focus first on CO_2 capture from concentrated flue sources that can be considered as "low-hanging fruits", provided there are plants operating and no other alternatives in the short term.

4 Biodiversity and land use implications of CO_2 transport and storage

The transport and geologic storage of captured CO_2 is a fundamental component of CCS, including for BECCS and DACCS. Transportation can occur in a network of pipelines, using shipping or other modalities (rail freight, truck etc).

Transportation of CO_2 is a well understood process that has been taking place in Norway and North America for several decades. CO_2 transport by pipeline is present in existing CCUS projects (*e.g.*, Snøhvit and Sleipner), but CO_2 transport by ship will be crucial to enable projects to become operational.

The development of infrastructure networks to connect industrial 'clusters' with other CO_2 capture sites and finally to CO_2 storage sites and across international borders is key to progress CCS in Europe. Such CO_2 transport infrastructure can serve as backbone for industrial decarbonisation, delivering negative emissions and enabling the delivery of early, large quantities of clean hydrogen from reformed natural gas with CCS.

Finally, CO_2 can be stored in geological formations, but also in mineral carbonates, for instance, in natural silica minerals[1]. Mineral carbonation involves converting CO_2 to solid inorganic carbonates using chemical reactions. CO_2 would not be released to the atmosphere after carbonation; thus, the produced silica and carbonates are stable over long-time scales and can be disposed of or re-used for construction purposes.

4.1 Pipeline transport of CO_2

Depending on the location of captured CO_2 and suitable sites of geologic storage, long pipelines may be necessary for the transport of CO_2. Pipeline transport is particularly suited for the transport of large quantities of CO_2, for instance from industrial clusters, because pipelines, despite high fixed costs, benefit from substantial economies of scale.

Pipelines require the clearing of land corridors, both for the construction of the pipeline and to ensure access for ongoing maintenance and monitoring. This can result in disruption to existing ecosystems as well as fragmentation of habitats and introduction of invasive species. However, there is limited research on the biodiversity impacts of pipelines, particularly studies that assess both baseline levels of biodiversity prior to the pipeline construction, and then follow the change in biodiversity through the pipeline's lifetime (Richardson et al., 2017).

One study conducted in the coastal town of Clonakilty Bay in Ireland showed a good recovery of ragworms and molluscs following a

[1] This does not cover deep geological carbonation or dissolution in pore water.

pipeline construction. The study found a lower figure of wading birds and a higher figure of roosting birds than expected (Lewis et al., 2003).

The German gas transmission operator OGE plans to develop a CO_2 pipeline for steel, cement, lime producers, power plant operators and chemical companies. The initial pipeline would be 1,000 km long with the first part scheduled for commissioning from 2028 for 18 million tonnes of CO_2 transported per year. The pipeline would link areas like Dortmund and Duisburg, in the industrial Ruhr, to Wolfsburg and the coastal city of Wilhelmshaven in the North Sea (OGE, 2022).

Based on the Cortez CO_2 pipeline in the United States that transports 20 million tonnes of CO_2 per year, an estimation of the outside diameter could be 76.2 centimetres (IPCC, 2005) for an approximative total surface of 76.2 hectares. As the average growing stock density amounts to 163m^3/ha in Europe (European Environmental Agency, 2021), an initial CO_2 infrastructure, for a country like Germany, could use the equivalent of 12,400 m^3 of growing stock.

This measure is only indicative as it does not reflect the nature of the land used for pipeline construction, the effective diameter of the pipeline or whether the pipeline will be buried or not. It is worth mentioning that onshore lines are usually buried, while offshore lines are almost always buried in shallow water. Moreover, vegetation can be restored if the pipeline is buried (IPCC, 2005).

Biodiversity impacts can be reduced by

- minimising corridors;
- using trenchless underground or elevated pipelines to minimise corridor fragmentation;
- monitoring actively and restoring of disturbed land with native species;
- facilitating industrial hubs to avoid the dispersion of emitters;
- facilitating the location of factories near coastlines; and
- timing and rerouting construction to minimise impacts on existing ecosystems.

4.2 Other forms of CO_2 transport

Other means of CO_2 transport include mainly ships, barges, trains, and trucks. Due to the high complexity of the measurement, the research gaps in this field, and the limited information available, it is difficult to give an estimation of the impact of these activities in terms of biodiversity and land use. Further research is needed in that field.

4.3 Offshore transport, injection, and storage of CO_2

The injection of CO_2 in geological formations for permanent storage is a safe, mature and tried technology (ZEP, 2019). Proper surveying, construction, and monitoring is necessary to prevent CO2 leakage, and several commercial and research operations of CO2 $_s$torage have provided evidence and experience that this can be done safely and comprehensively, allowing both the risk and impact of leakage to be minimised (Jenkins et al., 2015). A good overview of different options to store CO_2 in the subsurface is well illustrated in IPCC (2005).

While European CO_2 storage projects are currently focused on the offshore area (North Sea basin with an estimated storage capacity of about 300 Gt), there is also storage potential onshore. Siting of storage, like any infrastructure project, needs to take into consideration local land and biodiversity condition to minimise impact on local ecosystems.

The transport and storage of CO_2 into offshore geologic formations requires particular precaution to prevent CO_2 leakage, as seawater can be corrosive to pipelines and injection equipment. CO_2 leakage into the marine environment, while unlikely, can increase the local acidity of the water, thus disrupting the local ecosystem, decreasing calcification of marine organism shells, and lowering nutrient availability (Carruthers, 2014).

5 Biodiversity and land use implications of biomass use for BECCS

Biomass is an integral part of Bioenergy with carbon capture and storage (BECCS), replacing fossil fuels and feedstocks used in energy and industrial production processes. This section provides an overview of BECCS applications, a summary of assessments of biomass availability, and characteristics and considerations of specific biomass options for BECCS.

The figure below describes the different sources of biomass:

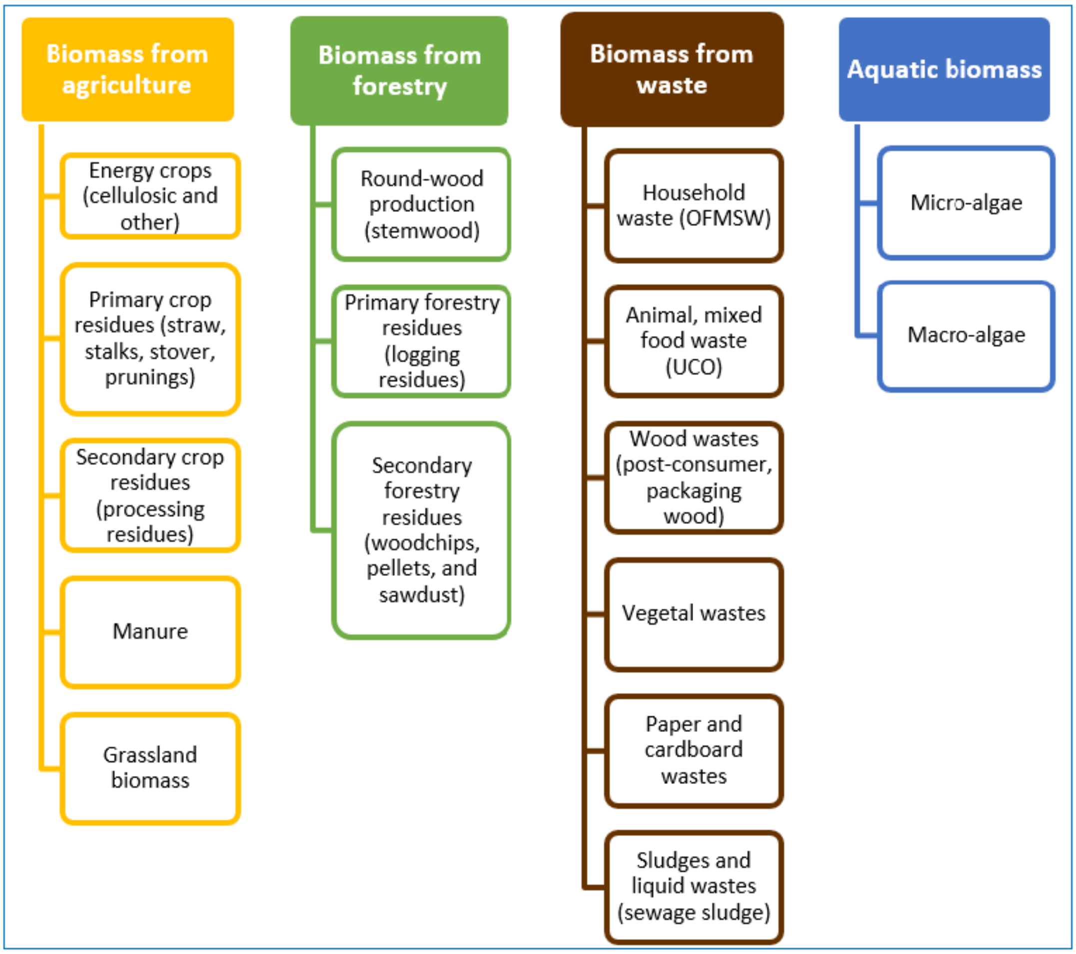

Figure 1: Overview of different types of biomasses (European Commission, 2017)

5.1 Overview of BECCS applications

BECCS can be used to mitigate CO_2 emissions in a wide range of processes. While early attention on BECCS focused on its use in the power sector, as reflected in (IPCC, 2015). BECCS can be used in more targeted industrial applications, where decarbonisation is more difficult.

This includes the use of CCS in pre-existing biogenic industries, such as paper, ethanol, biogas, and waste-to-energy, the retrofitting of biomass and CCS to reduce net emissions of currently carbon-intensive industrial installations, such as steel and cement plants, as lower-carbon alternatives are developed; and the use of BECCS in so-called “biorefineries” to replace the production of fossil-based chemicals (Tanzer et al., 2021).

BECCS plays an increasingly important role in the transition towards a low-carbon economy. The application of BECCS is important for regions where biomass is abundant and used in various sectors. This abundance in Nordic countries, such as Sweden and Finland and Denmark, combined with an extremely large geological storage potential in Norway, provides optimal conditions to establish BECCS in these regions (Whiriskey, 2018). CCS technologies could reach an efficiency target of up to 99% for captured C_O2, and often use 90% as baseline indicator (MIT, 2021).

5.1.1 Potential in different industrial sectors

Research was conducted into the deployment of CCS, biomass and BECCS for the CO_2-emitting industrial sectors related to performance and costs. There is still a limited focus on applying biomass or BECCS in industry. BECCS could achieve negative emissions in the iron, steel, pulp, paper, and hydrogen sectors under 100 €/t CO_2. Introducing only CCS shows a CO_2 reduction potential of up to 74%. Biomass application could help reduce CO_2 emissions even further. However, as the heating values of biomass are lower than for fossil fuels, the substitution of those by biomass is limited (Yang et al., 2021a).

CO_2 mitigation potentials vary for each industrial sectors (Yang et al. 2021a), as indicated in the following table.

Table 1: CO_2 mitigation potentials and CO_2 reduction cost potentials for BECCS use in different industrial sectors (Yang et al. 2021a)

Sector	***CO_2 reduction range***	***CO_2 reduction potential***	***CO_2 reduction costs (incl. CO_2 transport, storage) EUR/t CO_2***
steel	1.4-2.7 t CO_2 /t steel	77 - 149%	< 70 (based on 4 Mt/a steel, blast furnace/basic oxygen furnace, biomass, amine CO_2 capture)
cement	0.7 t CO_2 / t cement	92%	< 60 (based on 1.36 Mt/a cement, biomass, amine CO_2 capture)
chemicals (reference: from crude oil)	0.2 t CO_2 /t crude oil	68%	< 20 (based on 20 Mt/a crude oil consumption, biomass gasification for H2, no CO_2 capture) < 110 (based on 20 Mt/a crude oil consumption, biomass gasification for Fischer-Tropsch, amine CO_2 capture)
pulp mills	1.9 t CO_2 /t pulp	1,663-2,548%[1]	< 90 (based on 0.8 Mt/a pulp, amine CO_2 capture)
hydrogen (reference: from SMR)	34.9 t CO_2 /t H2	313%	< 60 (based on 0.06 Mt/a H2, amine CO_2 capture) < 80 (based on 0.06 Mt/a H2, biomass gasification, amine CO_2 capture)

1: Since Yang et al (2021a) assume that biomass is carbon neutral and stack avoided emissions from exported electricity with physical emissions and removals the baseline case of paper production is calculated as having near or even below-zero CO_2. This is not indicative of physical carbon dioxide removal in the base case, but rather an accounting phenomenon.

Pulp and paper facilities have the greatest potential for BECCS from existing point sources with 62 Mt of CO_2 per year (Rosa et al., 2021). Another study puts the focus only on the comparison of different steel production routes (blast oxygen furnace, direct reduced iron, electric arc furnace) using biomass and CCS to gain negative CO_2 emissions (Yang et al., 2021b).

All different routes give CO_2 reduction costs lower than €100 per tonne of CO_2 and are consistent with the results of the table. The study states that steelmaking applying the route of direct reduced iron and the route of electric arc furnace with BECCS, combined with carbon neutral electricity offers the highest CO_2 mitigation potential at 146%. However, the lowest CO_2 reduction cost at €54 per tonne of CO_2 comes from Hisarna-blast oyxgen furnace combined with BECCS option (Yang et al., 2021b).

Results from (Alemena et al., 2022) support the deployment of BECCS due to its potential in terms of GHG emission reduction. The publication focused on the UK, where BECCS is estimated to provide between 20 and 70 Mt of negative CO_2 emissions per year by 2050. The options examined could remove 0.8 and 1.4 tonne of CO_2 per tonne of biomass as negative CO_2 emissions and contribute to meet 23% or more of the UK's CO_2 removal targets if all wheat straw and waste wood available in the UK were used for that purpose. Trade-offs between biomass use, energy output and CDR targets have been quantified. Operational decisions (e.g., increase of electricity production and decrease of heat production or combinations with hydrogen generation) and policy decisions play a key role in CDR yield and sustainability. Modular decentralised BECCS systems could provide flexibility and support regional development.

For some industry sectors, BECCS can result in negative CO_2 emissions. The total CO_2 reduction potential in industry could be in the range of 10.1 Gt/a by 2050, while (Hepburn et al., 2019) found a BECCS potential ranging between 0.5 and 5 Gt/a by 2050 at costs of $60 to $160. The life-cycle CO_2 mitigation potential of BECCS integration is theoretically possible with currently or nearly commercialised technologies (Tanzer, 2022).

However, the additional demand for biomass and electricity required for BECCS is substantial, particularly when high-quality biomass is required, such as charcoal for steel production. On the scale of EU production, retrofitting top gas recycling, CCS, and partial charcoal use into blast furnace steelmaking could lead to over 200Mt/year in CO_2 emission reduction, but would require the sourcing of 55 Mt of sustainable timber or 15% of the total EU forestry production.

TABLE 2: EU-scale emission mitigation, electricity use, and biomass demand of ambitious BECCS scenarios from Tanzer (2022)[2]

Industrial Production Technology	Biomass Use Scenario	EU Production	Decrease in CO_2 emissions	Potential Negative CO_2	Total Additional Electricity Demand	Total Additional Biomass Demand	
Blast Furnace- Basic Oxygen Furnace Steel (with top gas recycling in BECCS case)	Approx. 40% fuel replacement with charcoal	92	-229	-4.5	51	55	1.11
Midrex DRI-EAF Steel	100% fuel replacement with wood-based biogas	1	-1	-0.3	0	1	0.01
CEMII Cement	100% fuel replacement with charcoal	165	-170	-51.5	26	28	0.56
Bioethanol via Fementation of maize	100% fuel and feedstock replacement with stover	4	-10	-5.5	2	2	0.03
Merchant Hydrogen via steam methane reforming of natural gas	100% fuel/feedstock replacement with biomethane from anaerobic digestion of agricultural biowastes	1	-16	-5.9	6	25	0.46
Ammonia		42	-165	-41.0	33	130	2.34
Urea		5	-26	n.a.	2	9	0.16
Unit		***Mt/year***	***Mt/year***	***Mt/year***	***TWh/year***	***Mt dry/year***	***EJ/year***

The cement production stood at 171.5 Mt in the EU27 in 2020 (CEMBUREAU, 2022). 1 tonne of cement consumes 0.11 MWh of electricity and 0.7-1.5 MWh of primary energy for the combustion process (fuel consumption linked to oil equivalent). This ratio gives a primary energy requirement of 120 to 257 TWh for the combustion process only. If this requirement were only met by biomass, the EU cement would need 3% to 5 % of the biomass available in the EU based on (Panoutsou and Maniatis, 2021).

However, current combustion processes rely on fuel mixes. The main share of CO_2 emissions during the cement production process comes from the feedstock (*eg,* limestone). Limestone calcination emits approximately two thirds of total CO_2 emissions or approximately 0.81 tonne of CO_2 per tonne of cement. A third of the total CO_2 emissions is related to fuel. Fuel-related CO_2 emissions can therefore be reduced if the fuel is switched towards biomass or other types of renewable energy sources. Negative emissions are also possible in combination with BECCS. The CO_2 emissions from the feedstock can mainly be reduced by the deployment of CCS.

[2] These numbers should be interpreted as maximum, rather than realistic, potentials.

A LCA has to be performed for all BECCS processes to find out the carbon intensity of each stage in the supply chains and ensure that reductions in emissions due to biomass use and CCS are not coupled with substantial emission increases elsewhere. However, these LCAs should also include impact categories beyond greenhouse gas emissions, to assess impacts on land use and biodiversity and determine opportunities to reduce burden shifting.

5.2 Overview of biomass availability

In principle, the use biomass usage is essential to replace fossil-based feedstock and enable carbon-negative emissions. Biomass provides a wide range of various applications from pulp and paper, construction materials to bioenergy, feedstock for different chemicals and many others.

The Renewable Energy Directive (EUR-Lex, 2018) defines the sustainability of biomass through a set of criteria:

- Biomass must be used in installations producing electricity, heating and cooling or fuels with a total rated thermal input equal to or exceeding 20 MW in the case of solid biomass fuels, and with a total rated thermal input equal to or exceeding 2 MW in the case of gaseous biomass fuels.
- Monitoring or management plans must be in place to address the impacts on soil quality and soil carbon.
- Biomass is not made from raw material obtained from land with a high biodiversity value.
- Biomass is not made from raw material obtained from land with high-carbon stock (*eg,* large forests).
- Biomass is not made from raw material obtained from land that was previously peatland.
- Adequate measures are put in place regarding forest management.
- Biomass comes from a country with adequate climate and sustainable land protection legislation.
- Biofuel leads to greenhouse gas savings of 70% for electricity, heating, and cooling installations started in 2021.

The European Commission proposed a revision of the Directive in 2021 that would strengthen the current sustainability criteria for forest biomass (including primary, highly diverse forests and peatlands). Those strengthened criteria are applied to small-scale biomass-based heat and power installations below a total rated thermal capacity of 5 MW (European Commission, 2022).

In general, while the demand for biomass is theoretically very high, its availability is limited. A first limitation comes from its application as a food source for humans and animals. Biomass should never be used for non-food applications at the expense of food production. A second limitation comes from the discrepancy between available biomass, which can be used as a primary energy source, and the energy demand which is predicted to increase globally and can be required for industrial processes, like steelmaking, to substitute fossil feedstocks.

The availability of sustainable biomass will be heavily constrained, with estimates ranging between 100 and 200 exajoule (EJ) per year (amounting to 27,789 and 55,560 TWh per year) in 2050, accounting roughly for 10 to 20 gigajoule (GJ) per person per year (2.8 to 5.6 MWh per person per year) (Mortensen et al., 2020). The global primary energy demand is expected to increase to roughly 90

GJ/person/year (25 MWh/person/year) by 2050. Other studies confirm that the global primary energy demand will increase in the coming decades (IEA, 2020 and bp, 2019). The global primary energy consumption in 2019 was estimated at 162, 200 TWh (bp, 2020). The global primary energy consumption is forecasted to reach 186,080 TWh in 2030 and 197,710 TWh in 2040, an increase of roughly 21%.

In the EU, the total primary energy consumption stood at 17,417 TWh in 2019 down from 17,714 TWh in 2018. This figure is expected to decrease further to 13,118 TWh in 2030 (EEA, 2021). In 2018 the primary energy production from renewables and biofuels, on one side, and nuclear heat, on the other, amounted to 2,538 TWh and 2,326 TWh respectively. The share of low- and zero carbon primary energy production amounted to 13.5% compared to the total primary energy consumption in the EU.

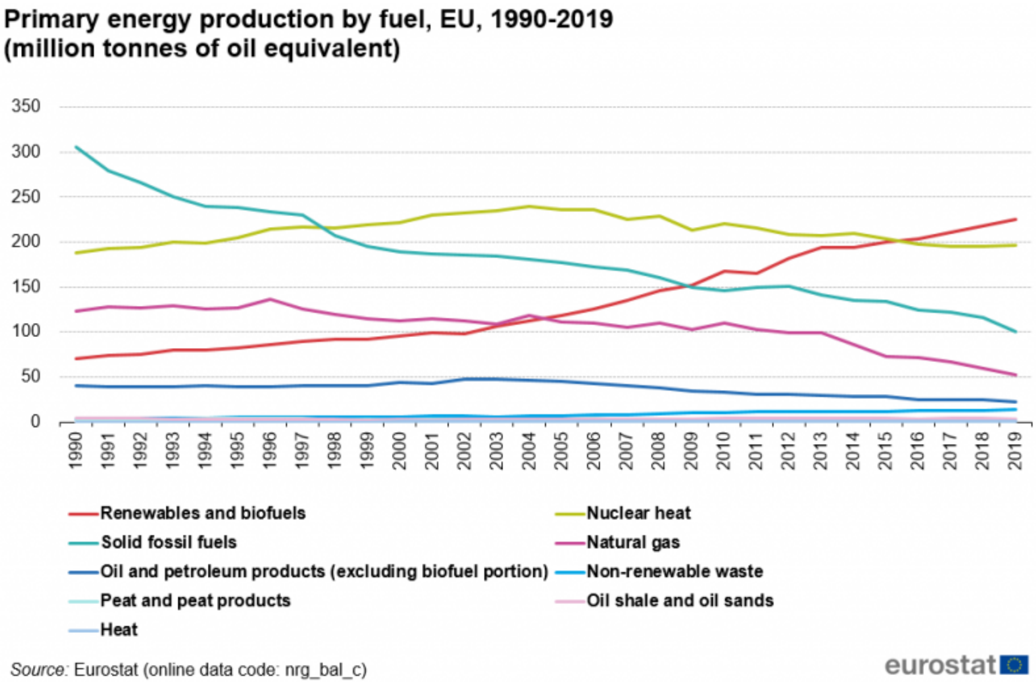

Figure 1: Primary energy production by fuel in the EU between 1990 and 2019 (Eurostat, 2022)

A rough estimation of thermal and electrical energy outputs cab be based on overall efficiencies of biomass-based CHP power plants ranging between 70% and 90% (IRENA, 2015).

A different study commissioned by the European Petroleum Refiners Association (Panoutsou and Maniatis, 2021), provides an overview of the potential availability of sustainable biomass in the EU and in the UK by 2030 and 2050. The study analyses sustainable biomass availability for all markets and estimates the amount that could be available for bioenergy, after excluding the demand from non-energy sectors. Bioenergy is used as the main category for all applications, like transport, heat, power, industry, agriculture, service and buildings.

Therefore, biofuels can be understood as a subcategory of bioenergy: biofuels can represent different biomass feedstocks for primary energy like wood, straw, energy crops etc. and they can represent energy carriers generated from the different biomass feedstocks like biogas, bio-oil etc. An analysis of biomass availability is needed to provide an overview of the advanced biofuel potentials for 2030 and 2050.

Sustainable biomass for bioenergy and non-bioenergy applications are estimated to range between 4,559 and 5,792 TWh (amounting to 0.98 to 1.2 Gt of dry biomass[3]) in 2030 and between 4,745 and 6,199 TWh (amounting to 1 to 1.3 Gt of dry biomass) in 2050. This gives an estimated amount for bioenergy ranging from 2,419 to 4,001 TWh (equivalent to 520 to 860 Mt of dry biomass) in 2030 and between 2,500 and 4,257 TWh (amounting to 539 to 915 Mt of dry biomass) in 2050. The advanced and waste-based biofuel production is predicted to range between 535 and 1,128 TWh in 2030 and between 826 and 2,047 TWh in 2050. The biomass potential of algae and other sustainable biomass-based feedstock is not considered in the study, and the real potential might be even higher in 2050.

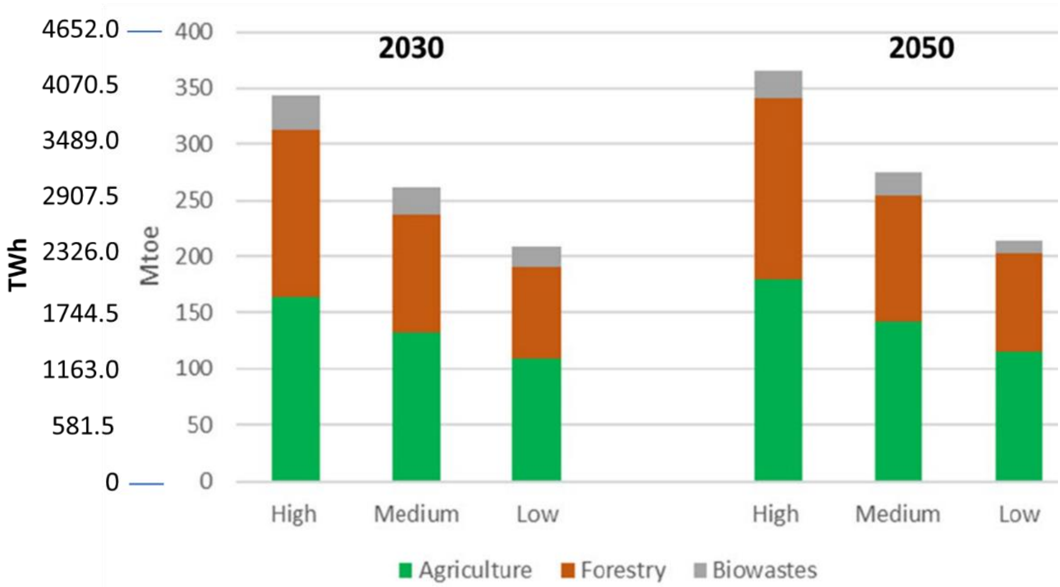

Figure 3: Different ranges of sustainable biomass availability for bioenergy in 2030 and 2050 in Mtoe (Panoutsou and Maniatis 2021) and in TWh[4]

Approximatively 39% of the land in the EU and the UK is used for agricultural production compared to a total area of 436,936 million hectares. 60% of the EU domestic biomass for energy purpose is based on wood (JRC, 2021). Finally, 38% of EU land is covered by forests (JRC, 2018a).

Even though the use of biomass can contribute to energy supply, there has also been criticism. Answering this question is very complex and gives an indication that there might be some technical, ecological, and economical restrictions defining the upper limit range for the biomass potential. Restrictions include indirect energy input to the growth of biomass (e.g., water, fertiliser, pesticides), ecological impacts from the supply of water, fertilisers, pesticides, and the release of ground GHG emissions as a consequence of harvesting and farming, impact from monoculture biomass. These limits should be further analysed.

[3] According to Panoutsou and Maniatis (2021), 2.45 Mt of dry biomass amounts approximately to 1 Mtoe and 0.21 Mt of dry biomass amounts approximately to 1 TWh.

[4] Unit conversion: 1 Mtoe = 11.63 TWh

Moreover, it is unlikely that the share of agricultural land dedicated to bioenergy or material use will increase as today's climate discussions go in the direction of a reduction in agricultural land.

The primary energy consumption of biomass stands at:

a) 15,444 TWh or 55,600 PJ globally in 2018 (World Bioenergy Association, 2020)
b) 1,453 TWh or 5,230 PJ in the EU in 2018 (World Bioenergy Association, 2020), an increase of 21% from 2007 (Raschka et al., 2012)
c) 317.5 TWh or 1,143 PJ in 2020 in Germany

A third limitation comes from the low specific energy yield of biomass related to land use, compared with other alternatives. A low specific energy yield results in a high land use to cover energy consumption. A higher land-use generally results in a higher negative impact on biodiversity.

The land demand for biomass to cover the primary energy demand should be put in relation to the following global figures from 2008 (UBA, 2013):

- total available land surface of 13,400 Mha (including deserts, mountains, and forests)
- total agricultural surface of 5,000 Mha
- total arable land surface of 1,445 Mha

The minimum land demand for biomass will probably exceed the total available land or at least take a significant part of it. The use of biomass risk to compete with food crops. However, the barrier of limited "traditional" biomass availability can be broken. In general, the land requirement of BECCS is defined as medium compared to other CDR alternatives (IEA, 2021).

The potential of biomass can increase significantly in the next decades if aquatic biomass becomes applicable and affordable for large-scale industrial deployments. The application of macroalgae and microalgae are highlighted as long-term opportunities for energy purposes, like advanced biofuels in Europe (EC, 2017). The current production is negligible with a global production at 30.45 Mt in 2015 (JRC, 2018a). The figure below gives an indication on the potential of aquatic biomass compared with biomass.

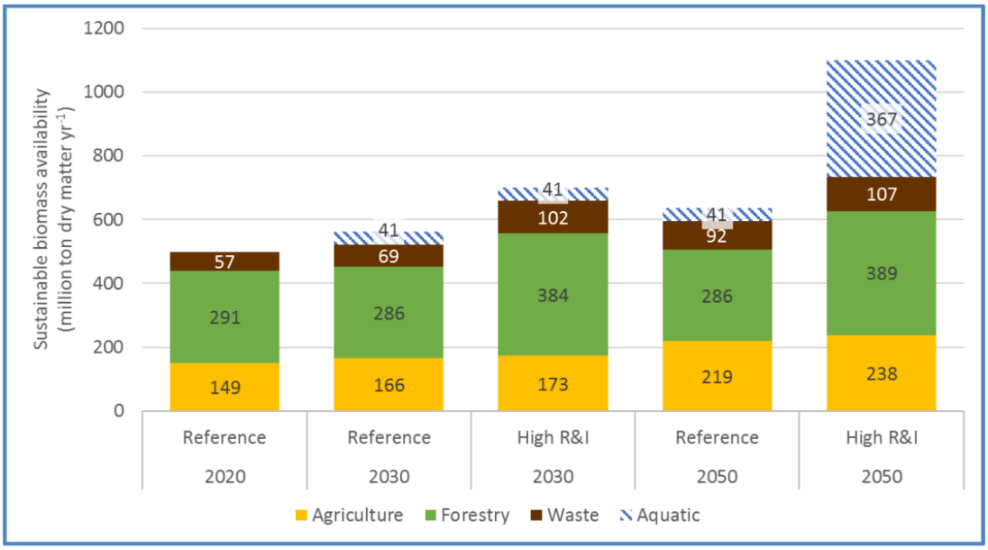

Figure 4: Sustainable biomass availability (EC, 2017), with higher uncertainties for aquatic biomass

5.3 Agricultural biomass

Most agricultural biomass is made of rice straw, rice hull, wheat straw, soya hull, maize (corn straw), sugar cane (bagasse), sorghum straw, barley straw, coconut straw, soybean straw, sunflower straw, and peanut shell (Saleem, 2022). The total global amount of agricultural biomass is estimated at 3,758 Mt/a, which gives an estimated energy content of 46,116 PJ or 12,810 TWh.

The total amount of agricultural biomass in the EU is estimated at 956 Mt/a (JRC, 2018b). 54% are primary products, like grains and fruits, and 46% are residues, like leaves and stems. Using the conversion factor in (Saleem, 2022), the EU agricultural biomass could produce 11,731 PJ or 3,259 TWh.

Manure is another component of agriculture biomass. It is a co-product of animal agriculture and can be considered as a resource for crop production or as a waste product (livestock manure, animal manure, liquid manure, bulky organic manure, compost manure, green manure) (Banja et al., 2019) Manure can also be used to produced biogas (Liebetrau et al. 2021 and Meyer et al., 2017).

The total production of biogas from all types of agriculture biomass in the EU in 2015 was 654 PJ (Meyer et al., 2017) providing 4.4% share in fuel gas use (Scarlat et al., 2018).

5.3.1 Land use and biodiversity implications

The specific energy yield of biomass compared to land-use is low. A comparison with the higher energy yield of hydrogen from low carbon or zero emission sources of non-biogenic origin is therefore interesting. The following examples describe this higher yield for renewable hydrogen produced with wind electricity (Enevoldsen et al., 2019 and IRENA, 2020).

a) The potential area for onshore wind power in Europe [5] is estimated at 4,895,560 km^2 and the installed wind power potential is estimated at 52,545,479 MW, which gives a specific installed electrical power of 10.7 MW/km^2. This amounts approximately to 2 wind turbines per km^2 at 4.5 MW per wind turbine. At a capacity factor of 30% (2,628 h/a) the electrical energy production is 138,090 TWh or 497,000 PJ. This gives a specific electrical energy yield of approximately 946 GJ/ha. (Enevoldsen et al., 2019) finds a lower value of specific installed wind power at 0.05 MW/ha. Using the same capacity factor, the specific electrical energy yield is 473 GJ/ha.
b) The specific electrical power demand related to land use for an electrolyser producing hydrogen ranges between 58.8 and 222.2 MW/ha depending on different studies quoted in (IRENA, 2020). Precise figures are not yet available since there has never been a large-scale electrolyser plant producing 100 MW or more. Based on the same capacity factor for wind power than in (Enevoldsen et al., 2019) and a specific electric power demand of electrolyser of 58.8 MW/ha, the specific electrical energy demand of electrolyser related to land use will amount to 154,579 MWh/ha. Assuming that an electrolyser has an

[5] This estimation of realisable potential should not be misconstrued as being the same as viable realisable potential. Non-restricted land might not be available for wind project development due to other land use conflicts, private ownership, and social opposition.

average electricity need of 4.5 kWh to generate 1 m^3 of hydrogen at standard temperature and pressure (STP) conditions of 1 bar and 0 °C (IRENA, 2018), the specific energy yield amounts to 437,953 GJ/ha related to the higher heating value (HHV) of hydrogen. If wind power plants are built in regions with much higher capacity factors, like in Scotland, the specific energy yield will increase significantly, that is the land use will fall for the same energy yield.

The example described in the previous section shows that the energy yield of biomass is significantly lower than for hydrogen. Renewable hydrogen and electricity produced by wind power use less land and have a lower impact on biodiversity. Moreover, it is possible to grow additional biomass, like forests, around onshore wind power plants. The Fasanerie wind farm in Germany represents a successful example with 22.5 million kilowatt hours of electricity produced per year (Renewable Energy Magazine, 2012).

5.3.2 Applications with CCS

There is no "fits-for-all" biomass type for all conversion processes and end-use applications. The type of biomass and waste feedstock varies depending on the production of each type of power, heat or biofuel. First-generation bioethanol is generated from annual food crops like sugarcane, corn, cereal crops, sugar beets or potatoes. Second-generation biofuels are made of lignocellulosic biomass from perennial crops, which are not food crops. Waste from agriculture, side-products of related industrial processing or livestock manure is mainly used for the production of biogas, followed by heat and power generation. There are different types of forest-based biomass. Low-grade non-merchantable wood (e.g., bark, wood chips – processed to wood pellets) is mainly used for the generation of heat and power.

5.3.3 Land use and biodiversity implications

Sunflower, sugar beet and sugarcane are taken as indicative biomass types of energy crops. The energy yield in the table below is the energy yield of crops and the energy yield of crop residues.

Land demands are measured at minimal values. It is assumed that the energy yield is completely transformed into thermal, chemical, or electrical power at an (unrealistic) conversion efficiency of 100%. The values of energy yields are average values depending on biomass type, climate conditions and other farming conditions, which all vary. Those figures provide an indication about land requirement.

Table 3: Energy yields data from Strezov (2019) and forestresearch (2021)[6]

		sunflower	*sugar beet*	*sugarcane*	*wood (SRC willow)*
typical values of *energy yield*	GJ/ha (crops, residue)	50.8	211.6	407.5	167
minimum land demand to cover primary energy consumption					
global (2019)	Mha	11,495	2,760	1,433	3,497
global (2040)	Mha	14,012	3,364	1,747	4,262
EU27 (2019)	Mha	1,234	296	154	382
*Germany**	Mha	232	55	29	71

The impact of agricultural biomass on biodiversity depends strongly on land use change scenarios. The conversion of natural areas to cropland, particularly for monoculture crop production, decreases local biodiversity, fosters habitat disruption and fragmentation, and creates nutrient unbalancing through decreased soil carbon and increased eutrophication. However, improvements in agricultural practices on existing land can improve soil quality, increase agricultural output, and foster biodiversity.

While the use of agricultural crop residues and manure may not result in direct changes in land use, indirect impacts must also be considered. Residues and manures are nutrient rich and can be used to improve soil quality. The quantity removed for fuel and feedstock production must not lead to soil quality degradation or its substitution with fertilisers, which would have indirect negative impacts on land use and biodiversity.

5.4 Municipal Solid Waste

Municipal solid waste (MSW), the solid waste material produced by households and commercial businesses, is another form of biomass available.

The typical global waste composition in 2018 consisted of 44% of food and green waste, 17% of paper and cardboard waste, 12% of plastic waste, 5% of glass waste, 4% of metal waste, 2% of wood, 2% of rubber and leather waste, and 14% of others (Kaza et al. 2018). This composition indicates that the share of waste from biogenic origin amounts to at least 45%, which explains why a large share of municipal waste is considered as biomass.

An estimated 1.6 billion tonnes of CO_2-equivalent GHG emissions were generated from municipal solid waste management (MSW) in 2016. This is driven primarily by the disposal of waste in open dumps and landfills without landfill gas collection systems. Such disposal accounts for about 5% of global emissions, according to the World Bank (Kaza et al. 2018). Without improvements in the sector, MSW–related emissions are anticipated to increase to 2.6 billion tonnes of CO_2-equivalents by 2050.

Waste-to-energy (WtE) facilities generated 31 TWh of electricity and 77 TWh of heat in the EU in 2012. The share of total energy from WtE plants is approximately 1% compared to the EU

[6] based on primary energy consumption in Germany, 11,784 PJ in 2021

final energy consumption of 41,447 PJ (11,513 TWh) in 2019 and would increase to approximately 2% in 2030 (EEA, 2021). In 2030, WtE facilities are forecasted to produce at least 54 TWh of electricity and 135 TWh of heat from, i.e. 680 PJ final energy production (IEA Bioenergy, 2017). This would be a WtE capacity increase by more than 100%.

As long as the share of waste management measures such as waste reduction, reuse or recycling cannot be increased significantly, the focus should be on the application of the most modern Waste-to-Energy technologies. In that context, the reduction of landfill and dumpsites capacities should be promoted. The International Solid Waste Association (ISWA) and UN Environment Programme (UNEP) estimate that there will be a 500% increase in WtE capacity in the next years as many developing countries intend to apply WtE to reduce their reliance on landfill and dumpsites (Kalogirou, 2018).

WtE plants are essential and will play a key role for future sustainable energy systems. WtE contributes to an improved waste management, especially due to increasing waste amounts, power and heat supply, CO_2 reduction through CCUS applications, and recovery of raw materials. WtE is a multi-output technology with high added value. The main advantages of WtE can be listed as follow (Kalogirou 2018):

- WtE technology has been known known for decades and WtE plants are operating well.
- GHG emissions from WtE plants are lower than those from landfills as emissions of methane at a global warming potential, which is approximately 21 times higher than CO_2.
- WtE plants use less land than landfills. The typical land requirement of WtE plants ranges between 0.04 and 0.07 km^2.
- WtE enables the recycling of ferrous and non-ferrous metals and granulates, which contributes to resources saving and GHG emission reduction.
- Approximately 50% of MSW is from a biogenic source.
- WtE is mostly used for cogeneration of heat and power, which replaces fossil sources and responds to some of the energy demand. They are 'must run' plants, which contribute to base loads.
- CO_2 emissions from WtE plants can be captured or utilised as feedstock. If stored permanently, the capture can even produce negative emissions.

5.4.1 Applications with CCS

Waste-to-Energy with CCS can significantly contribute to achieve negative emissions. According to the Renewable Energy Directive, the biodegradable fraction of municipal and industrial waste is considered biomass and represents therefore a renewable energy source.

The sources of this biogenic CO_2 are residual food scraps, textiles, wood and paper products that could not be sorted before incineration. Capturing the biogenic CO_2 removes *de facto* CO_2 from the atmosphere. Thus, half of the captured CO_2 from the waste-to-energy flue gases constitute net removal from the atmosphere, i.e., reductions that have a greater benefit than reducing emissions from fossil fuel combustion.

There is a growing demand for WtE capacity in Europe as the EU moves away from landfills and towards increased sorting and recycling. Assuming that ambitious recycling targets (65% material recycling and a reduction to 10% landfilling) will be achieved for commercial and industrial waste, there is a need for 142 million tons of residual waste treatment capacity in EU by 2035 (CEWEP, 2019).

In a scenario of 3.4 Gt MSW produced globally by 2050, 3.3 Gt of global CO_2 emissions could be avoided by deploying CCS. Half of these would be considered as negative emissions. In regions like the EU, where fossil sources are scarce, waste and WtE plants will become one of the main industrial CO_2 emission sources. There will also be MSW that will not be recycled. WtE combined with CCS is therefore essential for future energy production in the EU.

The EU has a current capacity of 100 Mt of waste treatment. The EU should build up an additional WtE capacity of approximately 40 Mt by 2035 and combine it with CCS. Residual waste treatment amounts to 142 Mt and BECCS represents 50% of the potential from WtE. The BECCS potential from WtE will amount to approximately 70 Mt per year by 2035.

5.4.2 Land use and biodiversity implications

There are few studies on the impact of waste-to-energy on land use and biodiversity. This impact is strongly dependent on the alternative waste disposal scenario. The direct land use implication of WtE depend on the specific configuration of the WtE plant (McCauley, 2009). WtE can reduce land use in cases where the waste would have otherwise gone to landfills. If WtE competes with recycling, it could indirectly lead to an increase in land use caused by larger material production.

WtE plants combined with CCS should therefore be deployed on a large scale. These plants should not compete with recycling activities.

5.5 Forestry biomass

The use of forestry biomass comes in wider perspective as it is not and should not only used for bioenergy purposes.

The application of forestry biomass depends on the trees. A single tree provides several raw materials in the form of wood product, by-products and side-streams (Stora Enso, 2022), *eg* wood material for construction, pulp for packaging and paper, chemicals to substitute graphite in anodes for Li-based batteries or generate polyacrylonitrile fibres. Many other applications exist. Side-streams, like wood chips, saw dust and bark, can be used for bioenergy. Forests themselves are considered as large carbon-sinks. Additionally, forests offer recreational opportunities.

A comprehensive overview of most of the forest-based biomass applications is shown here which is a summary from (Kellomäki et al., 2013), (Nicholls et al., 2018) and (WWF, 2022)

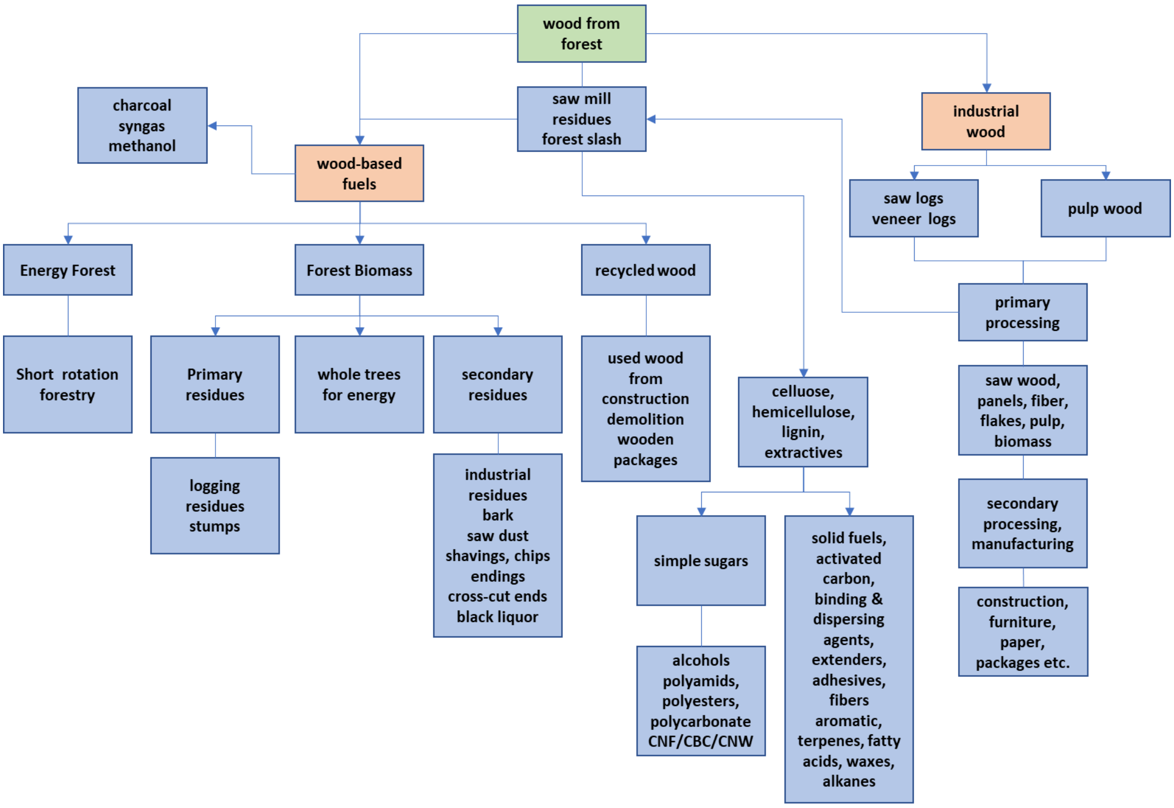

Figure 5: Overview of applications of forest-based biomass as summary from Kellomäki et al. (2013), Nicholls et al. (2018), and WWF (2022).

5.5.1 Applications with CCS

Forest biomass combined with CCS can lead to carbon-negative emissions for industries like pulp, paper, or steel. Wood's properties allow for an optimal utilisation in products like pulp, paper, and packaging. Wood is made of fibres that are needed for pulp, lignin, hemicelluloses, and bark. Papermaking is an energy intensive process that mostly requires steam, for drying and heating purposes, and electricity for motors.

In Nordic countries the favoured power plant set-up is to use a cogeneration process with a multifuel boiler and a turbine generating electricity, especially for integrated pulp and paper production. The multi-fuel boiler and the recovery boiler use most parts available inside the biomass (typically 90%), such as lignin, bark, production rejects (*e.g.,* shives), and energy rich sludges of effluent treatment plants.

The remaining demand is met by externally available biomass, mostly forest residuals and saw dust from sawmills. As the biomass flows do not always match the power plant needs, there is an active biofuel trading system between pulp and paper mills, sawmills, and community biomass power plants. The reason for that system is that the storage time of biofuels is limited due to space needs and the fuel quality in mill fuel yards. Active biofuel trading in a region allows for the optimal distribution of biomass.

Multi fuel boilers are complex to operate and have heavy investments in terms of capital expenditure. However, they have proven over time their benefits in terms of fuel flexibility. Fossil fuels, like natural gas and coal, can be fired in emergency situations. If available, recycled wood or plastic rejects (RDF) can be used as complementary fuels. There is a limitation, however, as these fuels tend to cause corrosion in the boiler.

CO_2 emissions could be reduced by 41.6 Mt by 2050, the equivalent of 65% of emissions in the Brazilian steel sector, by recycling steel from scrap and using charcoal for the blast furnace. Marginal costs would be close to zero (Souza and Pacca, 2021). The proposed use of charcoal is considered as a complementary strategy in this set-up.

There are limits to the possible use of biomass even though some processes using biomass and CCS in the steel industry promise lower CO_2 reduction costs and higher CO_2 mitigation effects. Carbon from biomass is less efficient than carbon from fossil feedstock: requirements in terms of carbon for biomass in blast furnaces are approximately 10% higher than for fossil feedstocks (Orre et al, 2021).

Between 2010 and 2019, the hot metal production (crude steel by basic oxygen furnace and others) in the EU ranged between 92.4 and 101.8 Mt per year (Eurofer, 2020). Based on an average hot metal production for steelmaking of 100 Mt per year and approximately 456 kg of carbon from fossil feedstock per tonne of hot metal would give a 45.6 Mt demand for carbon from fossil feedstock per year. Since the biogenic carbon consumption is 10% higher compared to carbon from fossil feedstock, the quantity of carbon from biomass amounts to approximately 500 kg to produce 1 tonne of hot metal.

The carbon content of biomass depends on the type of biomass: it ranges between 37 and 49 ma.-% of dry biomass. Assuming a carbon content of 40% in dry biomass, it would need approximately 1,250 kg of biomass per tonne of hot metal. If the fossil feedstock is substituted by 100% biomass, the total biomass quantity needed will amount to 125 Mt per year to produce 100 Mt of hot metal per year. 125 Mt of biomass per year means that more than 12% of the potential biomass availability (Panoutsou and Maniatis, 2021) would be consumed for the sole purpose of steelmaking.

This estimation does not include additional CO_2 emissions and other impacts, such as the effect on biodiversity during all stages of the supply chain, including transport, drying and other processing steps of biomass.

5.5.2 Land use and biodiversity implications

Forests play a fundamental role in the preservation of biodiversity. Forests provide habitats, regulate water and soil quality, and represent raw material and food for ecosystems. The European Green Deal recognises the importance of forests. The increase in forest coverage and the protection of old growth forests is a central part of the EU Biodiversity Strategy for 2030.

Forest biodiversity is in decline in Europe, threatened by climate change and commercial timber production (EASAC, 2017). The latter favours monocultural plantations, often of non-native species, increases land disturbance, and leads to habitat destruction. Increasing the forests' genetic diversity, lengthening the rotation periods of trees, and allowing deadwood to remain in forests can reduce these negative impacts. However, reduced timber production can be a potential negative consequence of these solutions.

There is no cohesive EU-level policy on sustainable forest management as EU countries are responsible for forest policies. EU countries also participate in pan-European reporting under the Ministerial Conference on the Protection of Forests in Europe (MCPFE) process. The MCPFE process has developed criteria and indicators for assessing if forests are sustainably managed (European

Commission, 2022). Sustainable forest management practices are commonly used in many EU countries, such as Sweden, Finland, and Germany.

5.6 Aquatic biomass

Algae are marine organisms that have the ability of photosynthesis and grow in a range of aquatic areas like seas, lakes, rivers, oceans or wastewater (Khan et al., 2018). Algae can be differentiated between red, brown, and green algae. They can also be defined as microalgae or macroalgae depending on by their sizes.

Microalgae are *"microscopic single cells and may be prokaryotic, similar to cyanobacteria (Chloroxybacteria), or eukaryotic, similar to green algae (Chlorophyta). Microalgae can be a rich source of carbon compounds, which can be utilized in biofuels, health supplements, pharmaceuticals, and cosmetics".* These cells *"have applications in wastewater treatment and atmospheric CO_2 mitigation".*

There is interest in their potential use for biofuel production as *"growth enhancement techniques and genetic engineering may be used to improve their potential"* (Khan et al., 2018). As has been mentioned previously, the large-scale deployment industrial of microalgae is expected in the next decades (JRC, 2017).

5.6.1 Applications with CCS

The cultivation of seaweed for commercial purposes mainly takes place in Asia, with a yearly production of 32 million tonnes fresh weight amounting to 99% of the global commercial production in 2018 (FAO, 2020). Seaweed for Europe states that the European nutrient-rich cold waters could provide ideal growing conditions for seaweed at large scale (Vincent et al., 2020). Seaweed aquaculture is still at a nascent stage in Europe, with a production of 300,000 tonnes per year in 2020. The potential in 2030 has been forecasted to 8 Mtpa (wet weight). There are currently no forecasts at European level beyond 2030.

A recent study showed that the production of biofuels from seaweed is not economically feasible. Increased cultivation areas and lower production costs could change that situation (Soleymani and Rosentrater, 2017).

A cascading biorefinery process could allow biofuels to be produced together with other seaweed-based products. In this type of refinery, multiple products are recovered from seaweed, where biological leftovers can be further processed to create a liquid or gaseous fuel (Balina et al., 2017). Hydrothermal Liquefaction (HTL) of wet seaweed in combination with plastics has been reported to be in operation, and gasification of seaweed for use in gas turbines has been envisaged, has not been demonstrated (Capron et al., 2020).

Water represents 90% of harvested seaweed. If seaweed is to be used as an energy feedstock in industrial processes, it would first need to be dried (using industrial waste heat, for instance). The dry weight could be composed of minerals (ash) up to 40-50%. However, the mineral content can easily be reduced via quick washing in 60°C freshwater (Nielsen et al., 2020). Hydrothermal Liquefaction of wet seaweed could represent an alternative to drying.

5.6.2 Land use and biodiversity implications

While aquatic biomass has minimal impact on onshore land use, challenges and uncertainties remain for maintaining biodiversity and preventing an excessive impact on marine ecosystems, e.g., through the proliferation of invasive species, reduced sunlight proliferation, eutrophication, or nutrient depletion (Fernand et al., 2017). Harvesting can also disturb local habitats. On the other hand, aquatic biomass cultivation has the potential to provide habitats with a variety of marine species. Improvements of ecosystem monitoring in aquaculture sites could increase the likelihood of positive, rather than negative, co-impacts (Brown et al., 2022).

Conclusions

An assessment of biodiversity is quite complex, global, or regional interactions are not well understood and assessment methods as standard are quite rare. Potential discrepancies between different models from the literature cannot be excluded. The data used serves as an estimation of future impacts. Therefore, a case-by-case careful analysis might be the most suitable approach.

For all processes, EU or national authorities should conduct an LCA for all parts in the supply chains, including transport and energy supply. Direct Air Capture might have a low land requirement compared to other CDR solutions. Carbon capture in industrial sites appear to require less land, though further evidence is needed. For highly efficient decarbonisation, EU funding for CCS should focus first on CO_2 capture from concentrated flue sources, provided there are plants operating and no other alternatives in the short term.

The impact of pipeline transport on biodiversity is mixed, with both positive and negative impacts described in the literature. An initial CO_2 pipeline, for a country like Germany, could use the equivalent of 12,400 m^3 of growing stock. However, vegetation should recover quickly if the pipeline is buried. Regarding the impact on biodiversity of CO_2 pipeline transport, the recommendations to EU and national authorities, and pipeline operators are:

- minimising corridors;
- using trenchless underground or elevated pipelines to minimise corridor fragmentation;
- monitoring actively and restoring of disturbed land with native species;
- facilitating industrial hubs to avoid the dispersion of emitters;
- facilitating emissions near coastlines;
- and timing and rerouting construction to minimise impacts on existing ecosystems.

Strict measures need to be put in place by operators to prevent CO_2 leakage during transport and storage. Seawater can be corrosive to pipelines and injection equipment and CO_2 leakage can disrupt the local ecosystem. Regarding CO_2 injection, proper surveying, construction, and monitoring should be put in place by competent authorities to prevent CO_2 leakage.

Biomass is a rare resource limited by multiple factors, such as competition for land, impacts on biodiversity, impacts on the land sink and water requirements. Biomass needs to respect several criteria to be considered as sustainable. Biomass should not be extracted at a faster rate than the land sink's capacity to regenerate itself. Biomass demand should be kept within manageable levels and avoid replacing solutions that have a better net CO_2 abatement or removal potential based on a life-cycle analysis. Finally, biomass should never be used at the expense of food production.

For many applications in various sectors, biomass is an essential raw material and feedstock. A growing number of applications, which have not used biomass as a typical feedstock, are going to replace stepwise their conventional fossil feedstock by biomass. Sustainable biomass will be important in many uses where it has not been used before. The different energy yields of biomass are significantly lower than the energy yield of hydrogen. Hydrogen made from an electrolyser and electricity from wind turbines have lower land-use, indicating a lower impact on biodiversity.

The biodiversity implications of agricultural biomass depend strongly on the land use change scenario. Further research should be conducted to measure the indirect impacts of biomass use knowing that residues and manure are rich in nutrients and can be used to improve soil quality. The application of BECCS is important for those regions where biomass is abundant and being used in various sectors. Looking at the Scandinavian region, Sweden, Finland and Denmark combined with a huge geological storage potential in Norway provide optimum conditions to establish BECCS.

EU policies should focus on the application of the most modern Waste-to-Energy technologies to expand Waste-to-Energy capacities. In that context, the reduction of landfill and dumpsites capacities should be promoted. Waste-to-Energy plants are 'must run' plants that also contribute to baseload energy production. The EU and Member States should consider incentivising the construction of an additional Waste-to-Energy capacity of approximately 40 Mt of waste treatment by 2035.

Biomass potential increase significantly in the next decades if aquatic biomass becomes applicable at affordable industrial large-scale deployments. Research should be conducted and funded at the EU level on the potential industrial deployment of seaweed for bioenergy and its impact on biodiversity.

If sustainable biomass is used in a process where biogenic CO_2 is captured by additional combination with CCS, it is even possible to realise CO_2 negative emissions. In this context, it is essential to reveal the decarbonation potential of biomass, its sustainability, and the overall specific costs related to the avoided amount of CO_2. The interactions of all stages of the supply chains for BECCS with biodiversity, land-use, water resources, food supply should be well understood and create of course challenges for LCA and evaluating negative CO_2 emissions. The biomass potential and the potential for BECCS can be extended by increased efforts on waste management in the short- und mid-term perspective as a "low-hanging-fruit" approach and by usage of aquatic biomass in the mid-term and long-term perspective if aquatic biomass becomes applicable at affordable industrial large-scale deployments.

Carbon capture and storage, along with BECCS and DACCS have complex relationships with land use and biodiversity that need further attention. The reduction of greenhouse gas emissions that results from CCS activities leads to reductions in climate change and pollution and can have positive impacts on preventing biodiversity loss. However, life cycle assessments of CCS/BECCS/DACS often focus on greenhouse gas emissions without accounting for land use, water use, ecotoxicities and other environmental stressors. Therefore, we provide the following recommendations for future CCS/BECCS/DACS projects: projects should systematically include a comprehensive life cycle assessment, including upstream supply chains of energy, biomass, and chemicals, and downstream supply chains of waste disposal and CO_2 transport and storage. A full set of environmental impact indicators should be included, not just greenhouse gas emissions.

The siting of CO_2 transport and storage must consider local implications for land use and biodiversity of specific siting options and seek to minimise land disturbance. Sustainability should be a 'gatekeeping' criterion for biomass used in BECCS.

A cascading principle, or merit order, should be applied to all biomass use, to ensure judicious application of limit biomass resources. This applies not only to "fresh" biomass, but also to waste biomass (including municipal waste), for which material recovery and reuse should be prioritised over energy recovery.

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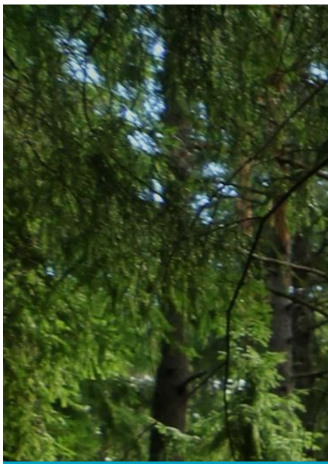

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