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Carbon Dioxide Removal (CDR) Environmental Life Cycle Assessment

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Executive summary

As defined by the IPCC, "Carbon Dioxide Removal (CDR) refers to anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological, geochemical, or chemical CO_2 sinks, but excludes natural CO_2 uptake not directly caused by human activities". Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) applied to fossil CO_2 do not qualify as removal methods. Both can only be part of CDR methods if the CO_2 is biogenic or directly captured from ambient air and stored durably in geological reservoirs or products (IPCC, 2022b).

The permanent removal of CO_2 (and other Greenhouse Gases (GHG)) from the atmosphere will be needed to reach stringent climate goals, i.e., limit global warming to well below two degrees. However, it is crucial that relying on CDR must not result in lowering ambitions to reduce GHG emissions. Nevertheless, CDR should be developed in the near term to enable its role in mid-term future to counterbalance hard-to-abate GHG emissions (e.g., emissions from agriculture, industry, and aviation), and in the long term to achieve net negative GHG emissions.

According to scenarios limiting global warming to well below two degrees, annual CDR in the order of Megatons will be needed on the Swiss national level, and in the order of Gigatons on the global level by mid of this century. Comparing the amounts of CDR needed in such "Paris compatible" scenarios with what has been announced on national levels or is part of national mitigation strategies, results in considerable "CDR gaps". There are currently few plans by countries to scale CDR above current levels, exposing a substantial shortfall. Today, CDR is still at its infancy and virtually all deployed CO_2 removal is associated with conventional management of land (or so-called "conventional" CDR methods), mainly via afforestation, reforestation, and management of existing forests.

The portfolio of CDR methods discussed is broad and includes further methods such as soil carbon sequestration, applications of biochar, bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), enhanced rock weathering, peatland and coastal wetland restoration, ocean alkalinity enhancement, ocean fertilization, and the use of timber as construction material. These methods largely differ in terms of development levels, costs, removal potentials, potential co-benefits and trade-offs, permanence of CO_2 removal and thus climate effectiveness. For many of those issues, reliable knowledge and evidence is missing today. These knowledge gaps should be filled quickly, as CDR implementation in the order of Megatons per year (domestically) and Gigatons per year (globally) requires massive upscaling and such large-scale implementation must not take place without a solid knowledge basis.

This report contributes to building such a knowledge basis by performing environmental Life Cycle Assessment (LCA) for several CDR methods potentially relevant from a Swiss perspective for removing CO_2 from the atmosphere – domestically and abroad. LCA is the method of choice for quantifying GHG emissions (and other environmental burdens) caused by CDR methods in a comprehensive way and thus for determining their net carbon removal effectiveness. Also, consistent methodologies for certification and monitoring, reporting and verification (MRV) of CDR often build on LCA.

Life Cycle Assessment (LCA)

The main goal of the LCA performed here is the quantification of "net carbon removal efficiencies"[1] of a range of CDR methods applying LCA methodology. Designing the LCA models in a parameterized way allows us to represent a broad range of boundary conditions in terms of, for example, energy supply options, geographical scope, transport modes and distances, etc., and to investigate the impact

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[1] Also referred to as "net carbon removal rate", "net CO_2 removal rate", "net CO_2 removal efficiency" or "net GHG removal efficiency" throughout this report. Specified here as: [(gross amount of CO_2 removed from the atmosphere for a period of 100 years or more) - life cycle GHG emissions of the CDR system)] / (gross amount of CO_2 removed from the atmosphere for a period of 100 years or more).

of different parameter settings on the LCA outcomes and thus the carbon removal effectiveness. The scope of the LCA here is limited to Direct Air Carbon Capture and Storage (DACCS) – low-temperature solid sorbent and high-temperature solvent based –, Bioenergy with Carbon Capture and Storage (BECCS) – using wood and municipal waste as fuels –, biochar applied as soil amendment, enhanced rock weathering, and ocean liming. Qualitative discussion, including an outline for a consistent framework for accounting for biogenic CO_2 fluxes, is performed for temporal storage of biogenic carbon by using wood as construction material. We perform attributional LCA of single, hypothetical CDR units, as if implemented and operated today, based on the currently available knowledge.[2]

Results

Under suitable framework conditions, all CDR methods analyzed can achieve very high net carbon removal rates in the order of 80-90% or even above, meaning that per ton of CO_2 permanently[3] removed from the atmosphere, 100-200 kilograms (or less) of CO_2-equivalents[4] are released by the "process chain" or "product system" required for a specific CDR method. Crucial for such high net removal rates are two factors:

1) Low-carbon energy supply, and
2) Minimizing transport distances for feedstock (biomass and rock material) and – less relevant – CO_2 (in case of geological storage).

If these two conditions can be met and purely based on net carbon removal rates, none of the analyzed CDR methods can be considered the preferred option and none of them should be excluded from further development and implementation. In practice, costs, potentials, side effects as well as technical and political barriers will determine preferred options.

If the two conditions highlighted above are not fulfilled, CO_2 removal becomes much less effective and, in some settings, the GHG emissions caused by the CDR system can even exceed the amount of CO_2 permanently removed. Most sensitive in this context are DACCS (due to a comparatively high energy demand), biochar-to-soil applications (due to a comparatively high amount of feedstock to be transported) and ocean liming (due to high energy demand and material transport). The BECCS and enhanced rock weathering systems represented in our LCA are less affected, as we assume that the energy for CO_2 capture needed by the wood and waste combustion plants is provided "internally", i.e., by these plants themselves reducing their heat and/or electricity output; and enhanced rock weathering exhibits a comparatively low energy demand.

Figure 0.1 shows life cycle GHG emissions and net CO_2 removal rates (tons of CO_2eq emitted per ton of CO_2 permanently removed from the atmosphere) of all CDR methods addressed in this report, with an "optimistic-realistic" parameter setting from the current Swiss perspective. It has to be kept in mind that these represent selected cases and that net CO_2 removal rates can vary over broad ranges, which are shown and discussed in section 4. It also needs to be considered, that the impact of co-products provided besides the CDR service by some of these CDR methods – e.g., heat and electricity generated by the MSW incineration – is not taken into account in this comparison. With the present parameter setting as summarized in the caption of Figure 0.1, the wood power plant with CCS, biochar applied as soil amendment, DACCS, and enhanced weathering exhibit very similar net carbon removal rates in a range of 0.83-0.91. Minor, but still main sources of GHG emissions are biomass supply and

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[2] It has to be acknowledged that attributional LCA is not appropriate for quantifying net removals for specific offset projects and credits (Brander, 2024), as attributional LCA does not quantify the total system-wide change in emissions or removals caused by an intervention.

[3] There is currently no definition of "permanence" of CO_2 removal commonly agreed upon. Here (most relevant for biochar-to-soil applications), we consider CO_2 being removed from the atmosphere for 100 years or more as permanent removal. Most recent evidence, provided by (Brunner, Hausfather and Knutti, 2024), showing that such a short period of time is insufficient in the context of net zero GHG emissions, could not be considered in our analysis due to temporal limitations.

[4] Cumulative greenhouse gas emissions are measured in terms of CO_2-equivalents (CO_2eq). We apply global warming potentials (GWP) for a time horizon of 100 years ("GWP_{100}").

transport for BECCS and biochar, CO_2 transport for DACCS, and rock transport for enhanced weathering. Net carbon removal rates of MSWI with CCS and ocean liming are slightly lower, namely 0.70 and 0.66, respectively. Non-captured direct fossil CO_2 emissions as well as CO_2 transport represent the main sources of GHG emissions of the MSWI with CCS. The main source of GHG emissions of ocean liming is quicklime production.

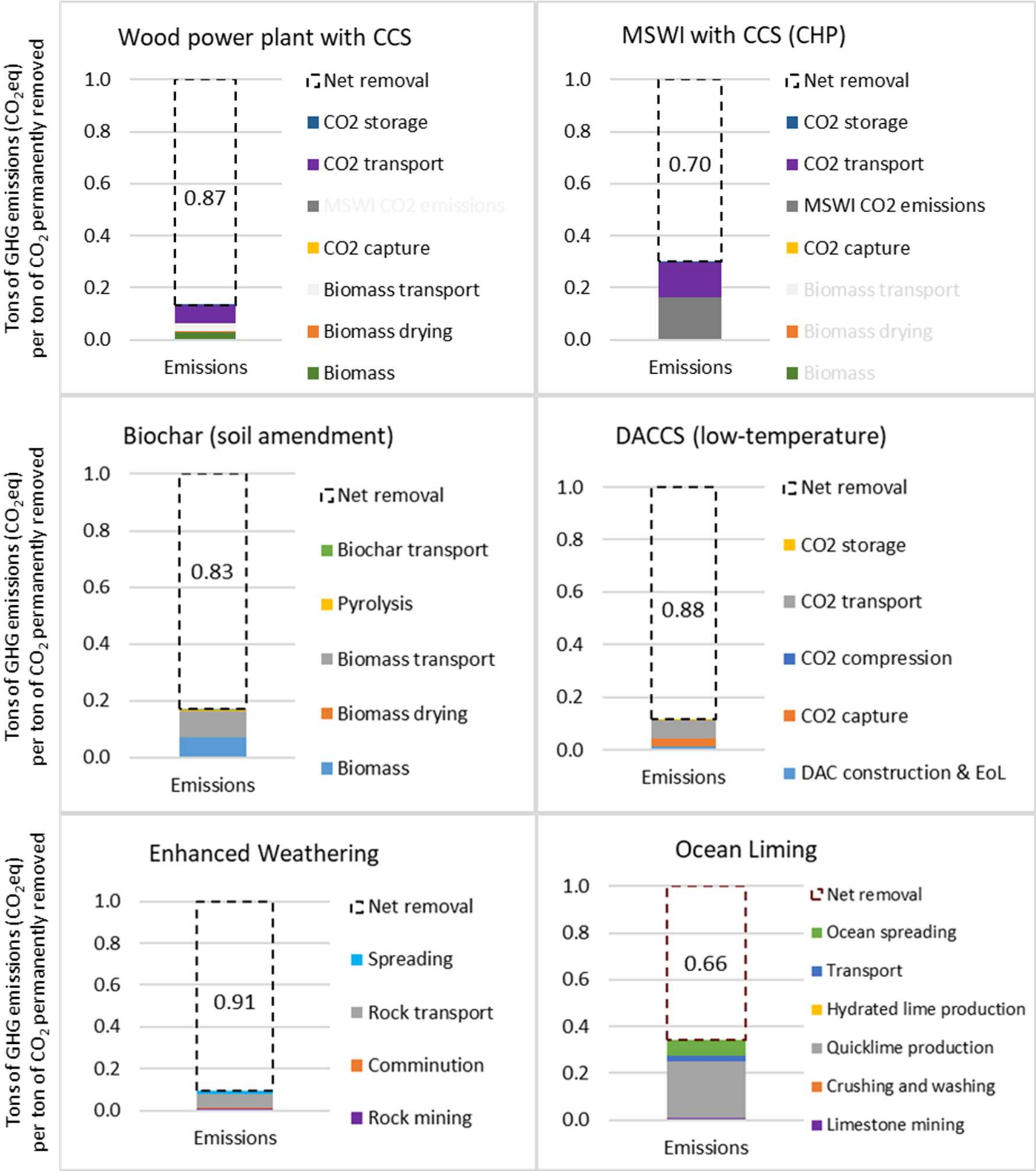

Figure 0.1: Life cycle GHG emissions of different CDR methods, evaluated with a “realistic-optimistic” parameter setting from a current Swiss perspective. MSWI: Municipal Solid Waste Incineration; DACCS: Direct Air Carbon Capture and Storage. All methods assumed to be applied in Switzerland, except Ocean Liming (Norway). Biogenic carbon content in the MSW: 52%; all GHG emissions associated with CO_2 transport and storage are assigned to this biogenic carbon fraction, thus to the CDR service. CO_2 capture rates: 90% at the wood power plant, 85% at the MSWI plant. Spruce used as biomass feedstock for biochar production and wood combustion. Geological CO_2 storage assumed to take place in Iceland for DACCS, wood combustion and MSWI with CCS. Transport of CO_2 via pipeline over 4000km; CO_2 storage depth: 3000m. DAC operated with Swiss grid electricity and waste heat. Plant-internal heat and power supply for CO_2 capture at the wood combustion and MSWI plants. Biomass and rock transport in the range of 100km. High-temperature heat supply for quicklime production from natural gas combustion. Specific CO_2 uptake of enhanced rock weathering: 0.35 t CO_2/t rock material. Dashed bar segments on top of each bar represent net CO_2 removal rates, i.e., the fraction of gross CO_2 permanently removed, which is not compensated by GHG emissions from the CDR product systems.

A question relevant from the Swiss perspective is whether capturing CO_2 in Switzerland (via biomass or waste combustion plants or direct air capture units) and permanently storing it abroad (e.g., in Iceland or Norway, where storage conditions are currently better known) makes sense from a life cycle perspective in terms of net carbon removal effectiveness. Our LCA results for DACCS and BECCS suggest that such a long-distance transport of CO_2 (even over thousands of kilometers) only causes relatively minor GHG emissions if pipelines are used for CO_2 transport. Other means of transport should only be used for transport of up to a few hundred kilometers during a transition period towards large-scale implementation and should be avoided in the long term due to associated higher GHG emissions.

Another question relevant from the Swiss perspective is for which purpose biomass should preferably be used. Due to its limited scope and the fact that such a question also touches upon policy relevant issues, this analysis cannot provide a conclusive answer. Only from a net carbon removal perspective, wood combustion with CCS for energy supply seems to be the most effective option to use woody (dry) biomass, as it removes most biogenic carbon from the atmosphere, and also provides low-carbon heat and electricity. Biochar used as soil amendment, however, may exhibit co-benefits in the agricultural system, or could pose risks for soils, both of which were not addressed in this analysis.

When interpreting the results presented in this report, different levels of uncertainties and reliability for specific CDR methods need to be taken into account – primarily since the development status and experience level with the methods considered in this analysis differs: while a few first BECCS and DACCS systems are already operated today, practical evidence and long-term experience is mostly lacking for biochar-to-soil applications and even more so for enhanced weathering and ocean liming. As the last three methods interact with the natural environment – the soil and the ocean – special caution is recommended before any large-scale implementation. Not only the climate effectiveness needs to be ensured over long periods of time, but also potential negative environmental side effects must be thoroughly investigated and kept to a minimum.

Recommendations for further research

In general, an LCA-based quantification of the climate effectiveness of all CDR methods is needed to allow for a comprehensive comparison of the different methods. Such an extension of scope should include CDR methods such as soil carbon sequestration, so-called “blue carbon” (i.e., ecosystem-based carbon removal in marine environments), ocean fertilization, peatland restoration, afforestation and reforestation, more BECCS options beyond wood and waste incineration, and long-term utilization of CO_2. Further, methods to remove greenhouse gases beyond CO_2 – methane and dinitrogen oxide – should be investigated. Such a more comprehensive evaluation should also follow best practices in LCA in dealing with co-products, which was considered out of scope of this work by its commissioner. Such an extension of scope should also focus on the aspect of durability of CO_2 removal and the differences between specific CDR methods in this context in a more meaningful way.

To enable quantification of environmental co-benefits and trade-offs, LCA should not only address GHG emissions and associated climate impacts, but other environmental burdens using common Life Cycle Impact Assessment midpoint categories such as particulate matter formation, ozone depletion, biodiversity loss, and acidification. An evaluation of many of these impact categories must apply regionalized impact assessment considering exposure of population and characteristics of ecosystems affected, as ecosystem damages and human health impacts most often depend on the location of burdens caused. The fact that CDR methods are quickly developing, and large-scale implementation will only take place years from now, should be considered by performing prospective LCA. For an evaluation of large-scale implementation, LCA should be embedded into a system analysis in which non-linearities and interactions between CDR, the energy system and the entire economy can be considered. Such a system perspective would also allow to quantify potential environmental burdens and benefits due to products and services beyond CO_2 removal, which some of the CDR methods provide, in a less-arbitrary way. Examples include the overall impact on the Swiss energy supply in case of large-scale BECCS or DACCS installation or potential impacts on Swiss agriculture by large-scale biochar-to-soil application. Further, the issue of permanence in terms of CO_2 removal needs to be addressed aiming for a commonly accepted way to address it in the context of LCA as well as MRV.

Zusammenfassung

Nach der IPCC-Definition bezieht sich der Begriff «Entfernung von CO_2» (englisch: Carbon Dioxide Removal (CDR)) auf anthropogene Aktivitäten, die CO_2 aus der Atmosphäre entfernen und dauerhaft in geologischen, terrestrischen oder ozeanischen Reservoiren oder in Produkten speichern. Der Begriff umfasst die bestehende und potenzielle anthropogene Verstärkung biologischer, geochemischer oder chemischer CO_2-Senken, schliesst jedoch die natürliche CO_2-Aufnahme aus, die nicht direkt durch menschliche Aktivitäten verursacht wird. CO_2-Abscheidung und -Speicherung (CCS) sowie CO_2-Abscheidung und -Nutzung (CCU), die auf fossiles CO_2 angewendet werden, gelten nicht als Abscheidungstechnologien. CCS und CCU können nur dann Teil von CDR-Prozessen sein, wenn das CO_2 biogen oder direkt aus der Umgebungsluft abgeschieden und dauerhaft in geologischen Lagerstätten oder in Produkten gespeichert wird (IPCC, 2022b).

Die dauerhafte Entfernung von CO_2 (und anderen Treibhausgasen (THG)) aus der Atmosphäre ist notwendig, um die strengen Klimaziele zu erreichen, d.h. die globale Erwärmung auf deutlich unter zwei Grad zu begrenzen. Es ist jedoch von entscheidender Bedeutung, dass der Einsatz von CDR nicht dazu führt, dass die Ambitionen zur Reduzierung der Treibhausgasemissionen nachlassen. Nichtsdestotrotz sollte CDR kurzfristig weiterentwickelt werden, um mittelfristig eine Rolle bei der Kompensation von schwer zu reduzierenden Treibhausgasemissionen (z.B. Emissionen aus Landwirtschaft, Industrie und Luftfahrt) zu spielen und langfristig eine Netto-Negativität der Treibhausgasemissionen zu erreichen.

Szenarien, welche die globale Erwärmung auf deutlich unter zwei Grad begrenzen, erfordern bis zur Mitte dieses Jahrhunderts auf nationaler Ebene in der Schweiz eine Entfernung von CO_2 in der Grössenordnung von Megatonnen pro Jahr und auf globaler Ebene in der Grössenordnung von Gigatonnen pro Jahr. Vergleicht man die in solchen „Paris-kompatiblen“ Szenarien benötigten CDR-Mengen mit dem, was auf nationaler Ebene angekündigt wurde oder Teil der nationalen THG-Minderungsstrategien ist, so ergeben sich erhebliche «CDR-Lücken», da derzeit nur wenige Länder Pläne haben, die CDR über das derzeitige Niveau hinaus zu erhöhen, was auf ein erhebliches Defizit hindeutet. Heute stecken die meisten CDR-Methoden noch in den Kinderschuhen, und praktisch die gesamte CO_2-Entfernung wird durch konventionelle Landbewirtschaftung (oder sogenannte «konventionelle» CDR-Methoden) erreicht, hauptsächlich durch Aufforstung, Wiederaufforstung und Bewirtschaftung bestehender Wälder.

Das Portfolio der diskutierten CDR-Methoden ist jedoch breit gefächert und umfasst weitere Methoden wie die Kohlenstoffbindung im Boden, Anwendungen von Pflanzenkohle, Bioenergie mit Kohlenstoffabscheidung und -speicherung (BECCS), direkte Kohlenstoffabscheidung und -speicherung aus der Luft (DACCS), verstärkte Gesteinsverwitterung, Renaturierung von Mooren und Küstenfeuchtgebieten, Erhöhung der Ozeanalkalinität, Ozeandüngung und die Verwendung von Holz als Baumaterial. Diese Methoden unterscheiden sich stark hinsichtlich Entwicklungsstand, Kosten, Abscheidungspotenzial, möglichen Nebenwirkungen, Dauerhaftigkeit der CO_2-Abscheidung und damit Klimawirksamkeit. Für viele dieser Fragen fehlen heute verlässliche Erkenntnisse und Belege. Diese Wissenslücken sollten rasch geschlossen werden, da eine Umsetzung von CDR in der Grössenordnung von Megatonnen pro Jahr (national) und Gigatonnen pro Jahr (global) eine massive Aufskalierung erfordert und eine solche grosstechnische Umsetzung nicht ohne eine solide Wissensbasis erfolgen darf.

Der vorliegende Bericht trägt zum Aufbau einer solchen Wissensbasis bei, indem er eine ökologische Lebenszyklusanalyse (LCA) für mehrere CDR-Methoden durchführt, die aus Schweizer Sicht für die Entfernung von CO_2 aus der Atmosphäre – im In- und Ausland – potenziell relevant sind. Die Ökobilanz ist die Methode der Wahl, um die Treibhausgasemissionen (und andere Umweltbelastungen), die durch CDR-Methoden verursacht werden, umfassend zu quantifizieren und damit die Nettoeffizienz

der Kohlenstoffentfernung zu bestimmen. Auch standardisierte Methoden für die Zertifizierung und Überwachung, Berichterstattung und Verifizierung (MRV) von CDR basieren häufig auf LCA.

Lebenszyklusanalyse – Ökobilanzen

Das Hauptziel der hier durchgeführten LCA ist die Quantifizierung der „Netto-CO_2-Entfernungseffizienz“[5] einer Reihe von CDR-Methoden unter Anwendung der LCA-Methodik. Das parametrisierte Design der Ökobilanzmodelle ermöglicht es, eine grosse Bandbreite von Randbedingungen abzubilden, z.B. in Bezug auf den geografischen Geltungsbereich, Energieversorgungsoptionen, Transportarten und -distanzen usw., und die Auswirkungen verschiedener Parametereinstellungen auf die Ökobilanzergebnisse und damit auf die Effizienz der Kohlenstoffentfernung zu untersuchen. Der Umfang der Ökobilanz beschränkt sich hier auf die direkte Kohlenstoffabscheidung und -speicherung in der Luft (DACCS) – Niedertemperatur- und Hochtemperatur-Verfahren –, Bioenergie mit Kohlenstoffabscheidung und -speicherung (BECCS) – unter Verwendung von Holz und Siedlungsabfällen als Brennstoffe –, Pflanzenkohle («biochar») zur Bodenverbesserung, verstärkte Gesteinsverwitterung und Meeres-Kalkanreicherung. Für die Zwischenspeicherung von biogenem Kohlenstoff durch die Verwendung von Holz als Baumaterial wird eine qualitative Diskussion geführt, die auch den Entwurf eines konsistenten Rahmens für die Bilanzierung biogener CO_2-Flüsse beinhaltet. Die Ökobilanzen werden für einzelne, hypothetische CDR-Anlagen erstellt, die auf der Grundlage des derzeit verfügbaren Wissens implementiert und betrieben würden.[6]

Ergebnisse

Unter geeigneten Bedingungen können alle untersuchten CDR-Methoden sehr hohe Netto-Kohlenstoffabscheidungsraten in der Grössenordnung von 80-90% oder mehr erreichen. Dies bedeutet, dass für jede Tonne CO_2, die der Atmosphäre dauerhaft[7] entzogen wird, 100-200 Kilogramm (oder weniger) CO_2-Äquivalente[8] durch die für eine bestimmte CDR-Methode erforderliche „Prozesskette“ oder das „Produktsystem“ freigesetzt werden. Zwei Faktoren sind für das Erreichen solch hoher Netto-Entfernungsraten ausschlaggebend:

1) Kohlenstoffarme Energieversorgung und
2) Minimierung der Transportwege für Rohstoffe (Biomasse und Gesteinsmaterial) und – etwas weniger relevant – für CO_2 (bei geologischer Speicherung).

Wenn diese beiden Bedingungen erfüllt werden können, kann keine der untersuchten CDR-Methoden als bevorzugte Option angesehen werden und keine sollte von der weiteren Entwicklung und Umsetzung ausgeschlossen werden. In der Praxis werden Kosten, Potenziale, Nebenwirkungen sowie technische und politische Hindernisse die bevorzugten Optionen bestimmen.

Wenn diese beiden Bedingungen nicht erfüllt sind, ist die CO_2-Entfernung deutlich weniger effektiv, und in einigen Fällen können die durch das CDR-System verursachten Treibhausgasemissionen sogar die Menge des dauerhaft entfernten CO_2 übersteigen. Am empfindlichsten sind in diesem Zusammenhang DACCS (wegen des vergleichsweise hohen Energiebedarfs), die Verwendung von

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[5] Hier berechnet als: [(Bruttomenge an CO_2, die der Atmosphäre über einen Zeitraum von 100 Jahren oder länger entzogen wird – Lebenszyklustreibhausgasemissionen des CDR-Systems)] / (Bruttomenge an CO_2, die der Atmosphäre über einen Zeitraum von 100 Jahren oder länger entzogen wird).

[6] Es muss eingeräumt werden, dass attributive LCA nicht geeignet ist, die Netto-Reduktion für spezifische Kompensationsprojekte und -gutschriften zu quantifizieren (Brander, 2024), da die attributive LCA nicht die gesamte systemweite Veränderung der Emissionen quantifiziert, die durch einen Eingriff oder eine Massnahme verursacht wird.

[7] Derzeit gibt es keine allgemein anerkannte Definition der „Dauerhaftigkeit“ der CO_2-Entfernung. In diesem Fall (der für die Anwendung von Pflanzenkohle im Boden am relevantesten ist) betrachten wir die Entfernung von CO_2 aus der Atmosphäre für 100 Jahre oder länger als dauerhaft. Neuere Evidenz (Brunner, Hausfather and Knutti, 2024), die zeigt, dass ein solch kurzer Zeitraum nicht ausreicht, um Netto-Null-Treibhausgasemissionen zu erreichen, konnten in unserer Analyse aufgrund zeitlicher Beschränkungen nicht mehr berücksichtigt werden.

[8] Die kumulierten Treibhausgasemissionen werden in CO_2-Äquivalenten (CO_2eq) gemessen. Wir verwenden das Treibhausgaspotenzial (Global Warming Potential, GWP) für einen Zeithorizont von 100 Jahren („GWP_{100}“).

Pflanzenkohle zur Bodenverbesserung (wegen der vergleichsweise großen Menge an zu transportierender Biomasse) und die Meeres-Kalkanreicherung (wegen des hohen Energiebedarfs und Materialtransports). Die in den vorliegenden Ökobilanzen dargestellten Systeme BECCS und verstärkte Gesteinsverwitterung sind davon weniger betroffen, da davon ausgegangen werden kann, dass die von den Holz- und Abfallverbrennungsanlagen für die CO_2-Abscheidung benötigte Energie „intern" bereitgestellt wird, d.h. durch diese Anlagen selbst, indem sie ihre Wärme- und/oder Stromproduktion reduzieren, und die verstärkte Gesteinsverwitterung einen vergleichsweise geringen Energiebedarf aufweist.

Abbildung 0.1 zeigt die Lebenszyklustreibhausgasemissionen und die Netto-CO_2-Entfernungsraten (emittierte Tonnen CO_2eq pro Tonne dauerhaft aus der Atmosphäre entnommenes CO_2) aller in diesem Bericht behandelten CDR-Methoden mit einer „optimistisch-realistischen" Parametereinstellung aus heutiger Schweizer Sicht. Dabei ist zu berücksichtigen, dass es sich um ausgewählte Fälle handelt und die Netto-CO_2-Entfernungsraten über weite Bereiche variieren können, wie in Kapitel 3 gezeigt und diskutiert wird. Es muss auch berücksichtigt werden, dass die Auswirkungen der Nebenprodukte, die einige dieser CDR-Methoden neben der CDR-Dienstleistung liefern – z.B. Wärme und Elektrizität aus der Verbrennung von Siedlungsabfällen – in diesem Vergleich nicht berücksichtigt sind. Mit der vorliegenden Parametrisierung, die in der Beschriftung von Abbildung 0.1 zusammengefasst ist, weisen das Holzkraftwerk mit CCS, Pflanzenkohle, DACCS und die beschleunigte Verwitterung sehr ähnliche Netto-CO_2-Entfernungen aus der Atmosphäre im Bereich von 0.83-0.91 auf. Geringe, aber dennoch relevante Quellen von Treibhausgasemissionen sind die Bereitstellung und der Transport von Biomasse bei BECCS und Pflanzenkohle, der CO_2-Transport bei DACCS und der Gesteinstransport bei der beschleunigten Verwitterung. Die Netto-CO_2-Entfernung von KVA mit CCS und Meeres-Kalkanreicherung sind mit 0.70 bzw. 0.66 etwas geringer. Nicht abgeschiedene direkte fossile CO_2-Emissionen und der CO_2-Transport sind die Hauptquellen der THG-Emissionen von KVA mit CCS. Die Hauptquelle der THG-Emissionen der Meeres-Kalkanreicherung ist die Herstellung von gebranntem Kalk.

Eine aus Schweizer Sicht relevante Frage ist, ob es aus der Lebenszyklus-Perspektive sinnvoll ist, CO_2 in der Schweiz abzuscheiden (in Biomasse- oder Abfallverbrennungsanlagen oder durch direkte Abscheidung aus der Luft) und im Ausland zu lagern (z.B. in Island oder Norwegen, wo die Lagerbedingungen derzeit besser bekannt sind), was die Netto-Effizienz der CO_2-Entfernung betrifft. Unsere LCA-Ergebnisse für DACCS und BECCS zeigen, dass ein solcher Ferntransport von CO_2 (selbst über Tausende von Kilometern) relativ geringe Treibhausgasemissionen verursacht, wenn für den CO_2-Transport Pipelines verwendet werden. Andere Transportmittel sollten nur für Transporte bis zu einigen hundert Kilometern in einer Übergangsphase bis zur grosstechnischen Umsetzung eingesetzt werden und wegen der damit verbundenen höheren Treibhausgasemissionen langfristig vermieden werden.

Eine weitere aus Schweizer Sicht relevante Frage ist die nach der bevorzugten Nutzung von Biomasse. Aufgrund des begrenzten Umfangs dieser Arbeit und der Tatsache, dass eine solche Frage auch politisch relevante Themen berührt, kann diese Analyse keine abschliessende Antwort geben. Lediglich aus der Perspektive der Netto-Kohlenstoffentfernung scheint die Holzverbrennung mit CCS die effektivste Option für die Nutzung von (trockener) holziger Biomasse zu sein, da sie den grössten Teil des biogenen Kohlenstoffs aus der Atmosphäre entfernt und gleichzeitig kohlenstoffarme Wärme und Elektrizität liefert. Die Verwendung von Pflanzenkohle als Bodenverbesserungsmittel kann jedoch zusätzliche Vorteile oder Risiken für das landwirtschaftliche System mit sich bringen, die in dieser Analyse nicht berücksichtigt wurden.

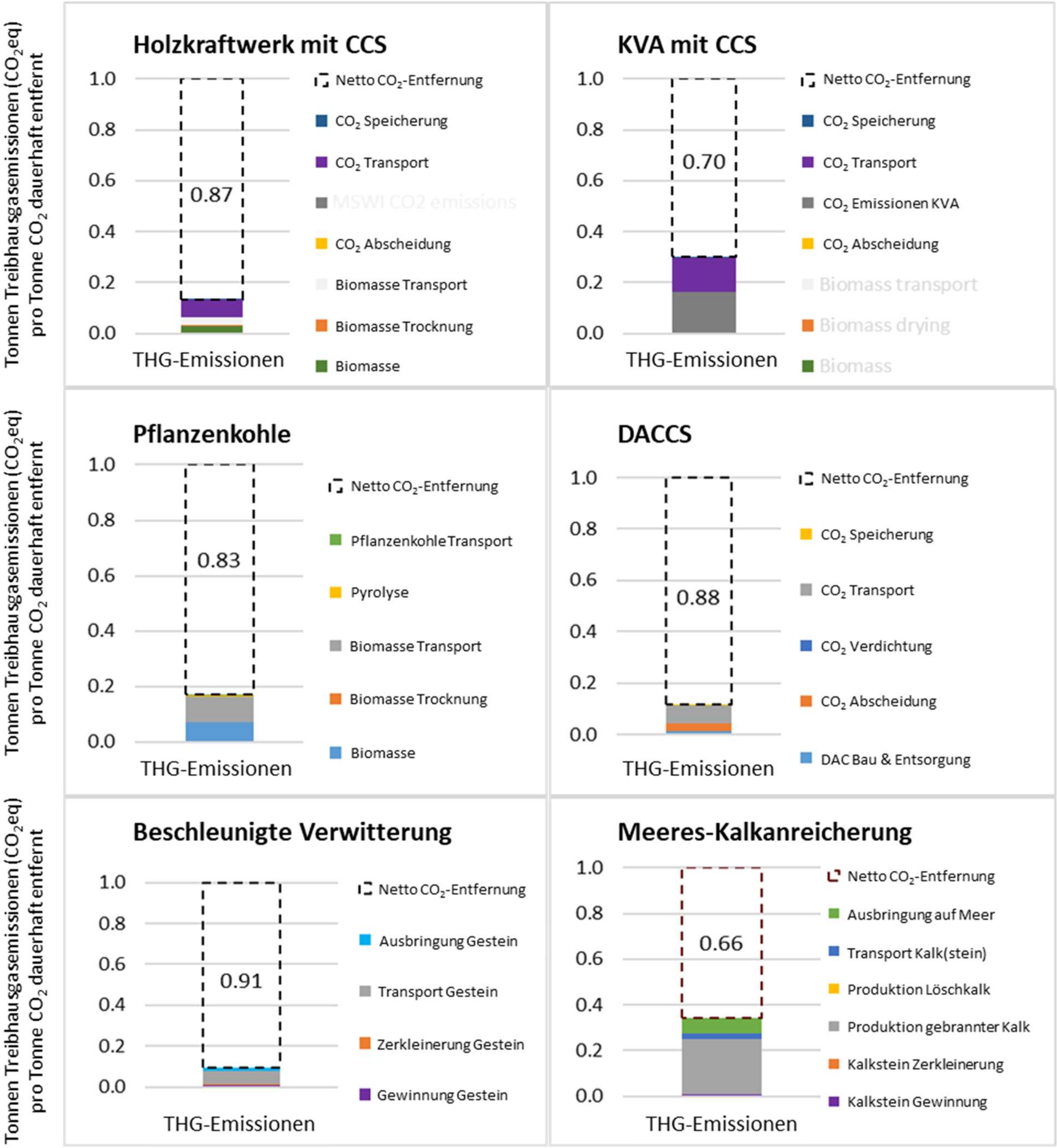

Abbildung 0.1: Lebenszyklus-Treibhausgasemissionen verschiedener CDR-Methoden, berechnet mit einer „realistisch-optimistischen" Parametereinstellung aus heutiger Sicht der Schweiz. KVA: Kehrichtverbrennungsanlage; DAC(CS): Direkte Abscheidung (und Speicherung) von Kohlendioxid aus der Luft; THG: Treibhausgas. Alle Methoden gehen von einer Anwendung in der Schweiz aus, mit Ausnahme von Meeres-Kalkanreicherung(«Ocean Liming», Norwegen). Biogener Kohlenstoffanteil im Siedlungsabfall: 52%; alle THG-Emissionen im Zusammenhang mit CO_2-Transport und -Speicherung werden diesem biogenen Kohlenstoffanteil und damit der CDR-Dienstleistung zugerechnet. CO_2-Abscheidungsraten: 90% im Holzkraftwerk, 85% in der KVA. Fichtenholz wird als Biomasse für die Biokohleproduktion und die Holzverbrennung verwendet. Geologische CO_2-Speicherung in Island für DACCS, Holzverbrennung und MSWI mit CCS angenommen. Transport des CO_2 über eine 4000 km lange Pipeline; CO_2-Speichertiefe: 3000 m. DAC wird mit Schweizer Netzstrom und Abwärme betrieben. Anlageninterne Wärme- und Stromversorgung für die CO_2-Abtrennung in den Holzverbrennungs- und KVA-Anlagen. Transport von Biomasse und Gestein im Bereich von rund 100 km. Hochtemperaturwärmeversorgung für die Brennkalkproduktion aus einer Erdgasverbrennung. Spezifische CO_2-Aufnahme durch verstärkte Gesteinsverwitterung: 0.35 t CO_2/t Gesteinsmaterial. Die gestrichelt umrahmten Balkenteile über jedem farbigen Balken stellen die Netto-CO_2-Entfernungsraten dar, d.h. den Anteil des dauerhaft entfernten Brutto-CO_2, der nicht durch THG-Emissionen aus den CDR-Produktsystemen kompensiert wird.

Bei der Interpretation der in diesem Bericht präsentierten Ergebnisse ist es wichtig, den unterschiedlichen Grad an Unsicherheit und Zuverlässigkeit spezifischer CDR-Methoden zu berücksichtigen, der hauptsächlich auf den Entwicklungsstand und die Komplexität der Methoden zurückzuführen ist: Während einige erste BECCS- und DACCS-Systeme heute bereits in Betrieb sind, fehlen praktische Langzeiterfahrungen für die Anwendung von Pflanzenkohle auf Böden und noch mehr für die beschleunigte Verwitterung und Kalkanreicherung von Meeren. Da die drei letztgenannten Methoden in Wechselwirkung mit der natürlichen Umwelt (Boden und Meer) stehen, ist vor einer grossflächigen Umsetzung besondere Vorsicht geboten. Nicht nur die Klimawirksamkeit muss über lange Zeiträume gewährleistet sein, auch mögliche negative Umweltauswirkungen müssen gründlich untersucht und minimiert werden.

Empfehlungen für weitere Forschung

Generell ist eine LCA-basierte Quantifizierung der Klimawirksamkeit aller CDR-Methoden erforderlich, um einen umfassenden Vergleich der verschiedenen Methoden zu ermöglichen. Eine solche Erweiterung des Anwendungsbereichs sollte CDR-Methoden wie die Kohlenstoffbindung im Boden, den sogenannten „blauen Kohlenstoff“ (d.h. die ökosystembasierte Kohlenstoffentfernung in der Meeresumwelt), die Ozeandüngung, die Renaturierung von Mooren, Aufforstung und Wiederaufforstung, weitere BECCS-Optionen, die über die Holz- und Abfallverbrennung hinausgehen, und die langfristige Nutzung von CO_2 einschliessen. Darüber hinaus sollten Methoden zur Beseitigung anderer Treibhausgase als CO_2 – Methan und Lachgas – untersucht werden. Eine solche umfassendere Bewertung sollte sich auch auf bewährte LCA-Praktiken im Zusammenhang mit der Behandlung von Nebenprodukten stützen, die vom Auftraggeber als ausserhalb des Rahmens dieser Arbeit betrachtet wurden. Eine solche Erweiterung des Umfangs sollte sich auch auf den Aspekt der Dauerhaftigkeit der CO_2-Entfernung sowie die Unterschiede zwischen spezifischen CDR-Methoden in diesem Zusammenhang konzentrieren – und zwar in einer aussagekräftigeren Weise, als dies im Rahmen dieser Arbeit möglich war.

Um den ökologischen Zusatznutzen und mögliche Zielkonflikte quantifizieren zu können, sollten in der Ökobilanz nicht nur die Treibhausgasemissionen und die damit verbundenen Klimawirkungen berücksichtigt werden, sondern auch andere Umweltbelastungen gemäß den in der Ökobilanz üblichen Wirkungskategorien wie Feinstaubbildung, Ozonabbau, Verlust an biologischer Vielfalt, Eutrophierung und Versauerung. Die Bewertung vieler dieser Wirkungskategorien erfordert jedoch eine regionalisierte Wirkungsabschätzung unter Berücksichtigung der Exposition der Bevölkerung und der Eigenschaften der betroffenen Ökosysteme, da die Schädigung der Ökosysteme und die Auswirkungen auf die menschliche Gesundheit in der Regel vom Ort der verursachten Belastungen abhängen. Bei der Durchführung einer prospektiven Ökobilanz sollte auch die Tatsache berücksichtigt werden, dass sich die CDR-Methoden rasch weiterentwickeln und eine grossmaßstäbliche Umsetzung erst in einigen Jahren erfolgen wird. Für die Bewertung einer grosstechnischen Umsetzung sollte die LCA in eine Systemanalyse eingebettet werden, in der Nichtlinearitäten und Wechselwirkungen zwischen CDR, dem Energiesystem und der Gesamtwirtschaft berücksichtigt werden können. Eine solche Systemperspektive würde auch eine weniger willkürliche Quantifizierung der potenziellen Umweltauswirkungen und -vorteile von Produkten und Dienstleistungen ermöglichen, die über die CO_2-Abscheidung hinausgehen und von einigen CDR-Methoden erzeugt werden. Beispiele hierfür sind die Gesamtauswirkungen auf die Schweizer Energieversorgung im Falle einer grosstechnischen BECCS- oder DACCS-Installation oder die potenziellen Auswirkungen auf die Schweizer Landwirtschaft im Falle einer großtechnischen Ausbringung von Pflanzenkohle auf den Boden. Darüber hinaus muss die Frage der Dauerhaftigkeit der CO_2-Abscheidung geklärt werden, um einen allgemein akzeptierten Weg zu finden, diese sowohl in der LCA als auch in Bezug auf Überwachung, Berichterstattung und Verifizierung zu berücksichtigen.

Résumé

Selon la définition du GIEC, "l'élimination du dioxyde de carbone (CDR) désigne les activités anthropiques qui éliminent le CO_2 de l'atmosphère et le stockent durablement dans des réservoirs géologiques, terrestres ou océaniques, ou dans des produits. Elle comprend l'amélioration anthropique existante et potentielle des puits biologiques, géochimiques ou chimiques de CO_2, mais exclut l'absorption naturelle de CO_2 qui n'est pas directement causée par les activités humaines". Le captage et le stockage du carbone (CCS) et le captage et l'utilisation du carbone (CCU) appliqués au CO_2 fossile ne sont pas considérés comme des technologies d'élimination. Le CCS et le CCU ne peuvent faire partie des méthodes CDR que si le CO_2 est biogénique ou directement capté dans l'air ambiant et stocké durablement dans des réservoirs ou des produits géologiques (IPCC, 2022b).

L'élimination permanente du CO_2 (et d'autres gaz à effet de serre (GES)) de l'atmosphère sera nécessaire pour atteindre des objectifs climatiques stricts, c'est-à-dire pour limiter le réchauffement de la planète à bien moins de deux degrés d'ici 2100. Toutefois, il est essentiel que le recours au CDR n'entraîne pas une diminution des ambitions en matière de réduction des émissions de gaz à effet de serre. Néanmoins, le CDR devrait être développé à court terme afin de pouvoir jouer un rôle à moyen terme pour contrebalancer les émissions de GES difficiles à supprimer (par exemple, les émissions provenant de l'agriculture, de l'industrie et de l'aviation), et à long terme pour parvenir à un niveau d'émissions de GES négatif.

Selon les scénarios qui limitent le réchauffement de la planète à un niveau bien inférieur à deux degrés, une réduction des émissions de carbone de l'ordre de quelques mégatonnes par an sera nécessaire au niveau national suisse, et de l'ordre de quelques gigatonnes par an au niveau mondial d'ici le milieu de ce siècle. Si l'on compare les quantités de CDR nécessaires dans ces scénarios dits "compatibles avec les accords de Paris" avec ce qui a été annoncé au niveau national ou ce qui fait partie des stratégies nationales d'atténuation, on constate des lacunes considérables en matière de CDR, étant donné que les pays n'ont actuellement que peu de projets visant à augmenter les CDR par rapport aux niveaux actuels, ce qui expose à un déficit important. Aujourd'hui, la CDR en est encore à ses balbutiements et la quasi-totalité de l'élimination du CO_2 déployée est associée à la gestion conventionnelle des terres (ou aux méthodes dites "conventionnelles" de CDR), principalement par le biais du boisement, du reboisement et de la gestion des forêts existantes.

Toutefois, le portefeuille des méthodes de réduction des émissions de carbone examinées est large et comprend d'autres méthodes telles que la séquestration du carbone dans le sol, la capture par pyrolyse de biomasse (« biochar » en anglais), la combustion ou gazéification de biomasse avec capture et stockage du carbone (BECCS), la capture et stockage direct du carbone atmosphérique (DACCS), l'altération forcée des roches, la restauration des tourbières et des zones humides côtières, l'amélioration de l'alcalinité des océans, la fertilisation des océans et l'utilisation du bois comme matériau de construction. Ces méthodes diffèrent largement en termes de niveaux de développement, de coûts, de potentiel d'élimination, de co-bénéfices et de compromis potentiels, de permanence de l'élimination du CO_2 et donc d'efficacité climatique. Pour bon nombre de ces questions, des connaissances et des preuves fiables font défaut aujourd'hui. Ces lacunes doivent être comblées rapidement, car la mise en œuvre de la réduction des émissions de carbone de l'ordre de mégatonnes par an (au niveau national) et de gigatonnes par an (au niveau mondial) nécessite une montée en puissance massive, et une telle mise en œuvre à grande échelle ne peut se faire sans une base de connaissances solide.

Le présent rapport contribue à la constitution d'une telle base de connaissances en réalisant une analyse du cycle de vie (ACV) de plusieurs méthodes CDR potentiellement pertinentes du point de vue de la Suisse pour éliminer le CO_2 de l'atmosphère - au niveau national et à l'étranger. L'ACV est la méthode de choix pour quantifier les émissions de GES (et d'autres charges environnementales) causées par les méthodes CDR de manière exhaustive et donc pour déterminer leur efficacité nette en matière d'élimination du carbone. En outre, les méthodologies cohérentes de certification et de surveillance, de déclaration et de vérification (MRV) de la CDR s'appuient souvent sur l'ACV.

Analyse du cycle de vie (ACV)

L'objectif principal de l'ACV réalisée ici est la quantification des "efficacités nettes d'élimination du carbone"[9] d'une série de méthodes CDR en appliquant la méthodologie de l'ACV. La conception de modèles d'ACV paramétrés nous permet de représenter un large éventail de conditions limites en termes, par exemple, de portée géographique, d'options d'approvisionnement en énergie, de modes et de distances de transport, etc. et d'étudier l'impact de différents paramètres sur les résultats de l'ACV et donc sur l'efficacité de l'élimination du carbone. Le champ d'application de l'ACV est ici limité au captage et au stockage du carbone dans l'air (DACCS) - à base de sorbants solides à basse température et de solvants à haute température -, à la bioénergie avec captage et stockage du carbone (BECCS) - utilisant le bois et les déchets municipaux comme combustibles -, au biochar appliqué comme amendement du sol, à l'amélioration de l'altération des roches, et au chaulage des océans. Une discussion qualitative, y compris une ébauche de cadre cohérent pour la comptabilisation des flux de CO_2 non-fossile, est menée pour le stockage temporel du carbone non-fossile en utilisant le bois comme matériau de construction. Nous réalisons une ACV attributionnelle d'unités CDR uniques et hypothétiques, telles qu'elles seraient mises en œuvre et exploitées aujourd'hui, sur la base des connaissances actuellement disponibles.[10]

Résultats

Dans de bonnes conditions, toutes les méthodes CDR analysées peuvent atteindre des taux nets d'élimination du carbone très élevés, de l'ordre de 80-90 %, voire plus, ce qui signifie que pour une tonne de CO_2 éliminée de l'atmosphère de manière permanente[11], 100 à 200 kilogrammes (ou moins) de CO_2-équivalents[12] sont rejetés par la chaîne d'approvisionnement du procédé une méthode CDR donnée. Deux facteurs sont essentiels pour obtenir des taux d'élimination nets aussi élevés :

1) L'approvisionnement en énergie à faible teneur en carbone, et
2) Minimiser les distances de transport des matières premières (biomasse et matériaux rocheux) et - ce qui est un peu moins important - du CO_2 (en cas de stockage géologique).

Si ces deux conditions peuvent être remplies et si l'on se base uniquement sur les taux nets d'élimination du carbone, aucune des méthodes CDR analysées ne peut être considérée comme l'option préférée et aucune d'entre elles ne devrait être exclue d'un développement et d'une mise en œuvre ultérieurs. Dans la pratique, les coûts, les potentiels, les effets secondaires ainsi que les obstacles techniques et politiques détermineront les options préférées.

Si les deux conditions susmentionnées ne sont pas remplies, l'élimination du CO_2 devient beaucoup moins efficace et, dans certains cas, les émissions de GES causées par le système CDR peuvent même dépasser la quantité de CO_2 définitivement éliminée. Les plus sensibles dans ce contexte sont le DACCS

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[9] Également appelé "taux net d'élimination du carbone", "taux net d'élimination du CO_2 ", "efficacité nette d'élimination du CO_2 " ou "efficacité nette d'élimination des GES" dans le présent rapport. Spécifié ici comme : [(quantité brute de CO_2 retirée de l'atmosphère pendant une période de 100 ans ou plus) - émissions de GES du cycle de vie du système CDR)] / (quantité brute de CO_2 retirée de l'atmosphère pendant 100 ans ou plus).

[10] Il faut reconnaître que l'ACV attributionnelle n'est pas appropriée pour quantifier les absorptions nettes pour des projets et des crédits de compensation spécifiques (Brander, 2024) car l'ACV attributionnelle ne quantifie pas le changement total d'émissions ou d'absorptions à l'échelle du système causé par une intervention ou une action.

[11] Il n'existe actuellement aucune définition de la "permanence" de l'élimination du CO_2 qui fasse l'objet d'un consensus. Dans le cas présent (plus pertinent pour les applications du biochar au sol), nous considérons que l'élimination du CO_2 de l'atmosphère pendant 100 ans ou plus est une élimination permanente. Les preuves les plus récentes, fournies par (Brunner, Hausfather et Knutti, 2024) montrant qu'une période aussi courte est insuffisante dans le contexte d'émissions nettes de GES nulles, n'a pas pu être prise en compte dans notre analyse en raison de limitations temporelles.

[12] Les émissions cumulées de gaz à effet de serre sont mesurées en termes d'équivalents CO_2 (CO_2 eq). Nous appliquons les potentiels de réchauffement global (PRG) pour un horizon temporel de 100 ans ("PRG_{100} ").

(en raison d'une demande d'énergie relativement élevée), les applications de biochar au sol (en raison d'une quantité relativement élevée de matières premières à transporter) et le chaulage des océans (en raison d'une demande d'énergie et d'un transport de matériaux élevés). Les systèmes BECCS et d'altération forcée des roches représentés dans notre ACV sont moins concernés, car nous supposons que l'énergie nécessaire au captage du CO_2 par les installations de combustion du bois et des déchets est fournie "en interne", c'est-à-dire par ces installations elles-mêmes qui réduisent leur production de chaleur et/ou d'électricité ; l'altération forcée des roches présente une demande d'énergie comparativement faible.

Figure 0.1 montre les émissions de GES sur le cycle de vie et les taux nets d'élimination du CO_2 (tonnes de CO_2 eq émises par tonne de CO_2 définitivement éliminée de l'atmosphère) de toutes les méthodes CDR abordées dans ce rapport, avec un paramétrage "optimiste-réaliste" du point de vue de la Suisse d'aujourd'hui. Il faut garder à l'esprit qu'il s'agit de cas sélectionnés et que les taux d'élimination nette du CO_2 peuvent varier dans de larges fourchettes, ce qui est montré et discuté dans la section 4. Il faut également tenir compte du fait que l'impact des coproduits fournis en plus du service CDR par certaines de ces méthodes CDR - par exemple la chaleur et l'électricité co-générées par l'incinération des déchets solides municipaux - n'est pas pris en compte dans cette comparaison.

Une question pertinente du point de vue suisse est de savoir si le captage du CO_2 en Suisse (par le biais d'installations de combustion de biomasse ou de déchets ou d'unités de captage direct de l'air) et son stockage permanent à l'étranger (par exemple, en Islande ou en Norvège, où les conditions de stockage sont actuellement mieux connues) se justifient du point de vue du cycle de vie en termes d'efficacité nette de l'élimination du carbone. Les résultats de notre ACV pour les systèmes DACCS et BECCS suggèrent qu'un tel transport de CO_2 sur de longues distances (même sur des milliers de kilomètres) n'entraîne que des émissions de GES relativement mineures si des pipelines sont utilisés pour le transport du CO_2. D'autres moyens de transport ne devraient être utilisés que pour le transport du CO_2. D'autres moyens de transport ne devraient être utilisés que pour le transport sur quelques centaines de kilomètres au cours d'une période de transition vers une mise en œuvre à grande échelle et devraient être évités à long terme en raison des émissions de gaz à effet de serre plus élevées qui y sont associées.

Une autre question pertinente du point de vue suisse est de savoir à quelles fins la biomasse devrait être utilisée de préférence. En raison de son champ d'application limité et du fait qu'une telle question touche également à des aspects politiques pertinents, cette analyse ne peut pas fournir de réponse concluante. Du seul point de vue de l'élimination nette du carbone, la combustion du bois avec CCS pour l'approvisionnement en énergie semble être l'option la plus efficace pour utiliser la biomasse ligneuse (sèche), car elle élimine la plus grande partie du carbone biogénique de l'atmosphère et fournit en même temps de la chaleur et de l'électricité à faible teneur en carbone. Le biochar utilisé comme amendement du sol peut toutefois présenter des avantages connexes dans le système agricole mais aussi des risques pour les sols, deux aspects qui n'ont pas été pris en compte dans cette analyse.

Lors de l'interprétation des résultats présentés dans ce rapport, il convient de tenir compte des différents niveaux d'incertitude et de fiabilité des méthodes spécifiques de CDR, principalement en raison de l'état d'avancement du développement et du niveau d'expérience des méthodes faisant l'objet de cette analyse : seulement quelques systèmes BECCS et DACCS sont exploités aujourd'hui, et les preuves pratiques et l'expérience à long terme manquent pour l'application de biochar au sol et encore plus pour l'altération forcée des roches et le chaulage des océans. Ces trois dernières méthodes interagissant avec l'environnement naturel - le sol et l'océan - il est recommandé de faire preuve d'une grande prudence avant toute mise en œuvre à grande échelle. Non seulement l'efficacité climatique doit être garantie sur de longues périodes, mais les effets secondaires négatifs potentiels sur l'environnement doivent être étudiés en profondeur et réduits au minimum.

Recommandations pour la poursuite de la recherche

En général, une quantification de l'efficacité climatique de toutes les méthodes de réduction des émissions de carbone basée sur l'analyse du cycle de vie est nécessaire pour permettre une comparaison complète des différentes méthodes. Une telle extension du champ d'application devrait inclure des méthodes de réduction des émissions de carbone telles que le stockage du carbone dans le sol, le "carbone bleu" (c'est-à-dire l'élimination du carbone dans les écosystèmes marins), la fertilisation des océans, la restauration des tourbières, le boisement et le reboisement, d'autres options BECCS au-delà de l'incinération du bois et des déchets, et l'utilisation à long terme du CO_2. En outre, il convient d'étudier les méthodes permettant d'éliminer les gaz à effet de serre autres que le CO_2, tels que le méthane et l'oxyde d'azote. Une telle évaluation plus complète devrait également suivre les meilleures pratiques en matière d'ACV dans le contexte du traitement des coproduits, qui a été considéré comme hors de portée de ce travail par son commanditaire. Une telle extension du champ d'application devrait également se concentrer sur l'aspect de la durabilité de l'élimination du CO_2 et sur les différences entre les méthodes CDR spécifiques dans ce contexte d'une manière plus significative que nous n'avons pu le faire dans le cadre de ce travail.

Pour permettre la quantification des avantages connexes pour l'environnement et des compromis potentiels, l'analyse du cycle de vie ne devrait pas seulement porter sur les émissions de GES et les incidences climatiques associées, mais aussi sur d'autres charges environnementales selon les catégories d'impact communes de l'analyse de l'impact du cycle de vie, telles que la formation de particules, l'appauvrissement de la couche d'ozone, la perte de biodiversité, l'eutrophisation et l'acidification des terres et des océans. L'évaluation d'un grand nombre de ces catégories d'impact doit toutefois s'appuyer sur une évaluation régionalisée de l'impact qui tienne compte de l'exposition de la population et des caractéristiques des écosystèmes touchés, étant donné que les dommages causés aux écosystèmes et les incidences sur la santé humaine dépendent le plus souvent de la distribution géographique des dommages causés. En outre, le fait que les méthodes CDR se développent rapidement et que la mise en œuvre à grande échelle n'aura lieu que dans plusieurs années doit être pris en compte dans la réalisation d'une ACV prospective. Pour l'évaluation de toute mise en œuvre à grande échelle, l'ACV devrait être intégrée dans une analyse de système dans laquelle les non-linéarités et les interactions entre le CDR, le système énergétique et l'ensemble de l'économie peuvent être prises en compte. Une telle perspective systémique permettrait également de quantifier de manière moins arbitraire les dommages et bénéfices environnementaux potentiels dus aux produits et services allant au-delà de l'élimination du CO_2, que certaines des méthodes CDR permettent d'obtenir. Il s'agit par exemple de l'impact global sur l'approvisionnement énergétique de la Suisse en cas d'installation à grande échelle de BECCS ou de DACCS, ou des impacts potentiels sur l'agriculture suisse d'une application à grande échelle de biochar au sol. En outre, la question de la permanence, la surveillance, la déclaration et la vérification de l'élimination du CO_2 doit être abordée en vue de trouver un moyen communément accepté de l'aborder dans le contexte de l'ACV.

Abbreviations

ATR	**Autothermal Reforming (of natural gas)**
BECCS	Bioenergy with Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCS	Carbon Capture and Storage
CEW	Coastal Enhanced Weathering
CHP	Combined Heat and Power generation
CDR	Carbon Dioxide Removal
C-RCA	Carbonated Recycled Concrete Aggregate
CRCF	Carbon Removals and Carbon Farming regulation
DACCS	Direct Air Carbon Capture and Storage
ERW	Enhanced Rock Weathering
ETS	Emission Trading System
EW	Enhanced Weathering
GHG	Greenhouse gas
GWP	Global Warming Potential
HTHP	High Temperature Heat Pump
HWP	Harvested Wood Product
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MRV	Monitoring, Reporting, Verification
MSWI	Municipal Solid Waste Incineration
NDC	Nationally Determined Contribution
NET	Negative Emission Technology
NGCC	Natural Gas Combined Cycle
NGGI	National Greenhouse Gas Inventories
OL	Ocean Liming
RCA	Recycled Concrete Aggregate
SCS	Soil Carbon Sequestration
SDO	Standard Developing Organization
SMR	Steam Methane Reforming (of Natural gas)
TRL	Technology Readiness Level
VCM	Voluntary Carbon Market
VVB	Validation and Verification Body

1 Preface and introduction

1.1 Motivation

Limiting global warming to well below two degrees while aiming for continuous economic growth worldwide will require not only a massive reduction of greenhouse gas (GHG) emissions globally by around mid of this century, but in addition also the active removal of greenhouse gases, predominantly CO_2, from the atmosphere (Masson-Delmotte *et al.*, 2018; IPCC, 2022b; Panos, Glynn, *et al.*, 2023). This also holds true for Switzerland: Achieving the net-zero CO_2 emission goal by 2050 will require Carbon Dioxide Removal (CDR)[13] in the order of several megatons per year (Kirchner *et al.*, 2020; Kemmler *et al.*, 2021; Panos *et al.*, 2021; Panos, Ramachandran, *et al.*, 2023). However, it is crucial that relying on CDR must not result in lowering ambitions to reduce GHG emissions (Chiquier *et al.*, 2022; Carton *et al.*, 2023; Ho, 2023). Latest developments and policies, however, show that unless global emissions in 2030 are brought below the levels implied by existing policies and current National Determined Contributions, it will become impossible to reach a pathway that would limit global warming to 1.5°C with no or limited overshoot, and strongly increase the challenge of limiting warming to 2°C (United Nations, 2024). Temperature overshoots, however, have consequences: Recent research shows that achieving net zero greenhouse gas emissions is critical to limit climate tipping risks (Möller *et al.*, 2024) and that global and regional climate change and associated risks after an overshoot are different from a world that avoids it (Schleussner *et al.*, 2024). Nevertheless, in the context of CDR, it is crucial that national climate policy frameworks will have to be expanded quickly to scale up CDR in time (Smith, 2021; Smith *et al.*, 2023).

The portfolio of CDR methods is broad, quickly developing, and includes biological, geochemical, and chemical options (section 2). Their characteristics are often fundamentally different. Which, in turn, can determine both net-effectiveness and permanence of CO_2 removal as well as environmental co-benefits and potential negative side effects (Cobo *et al.*, 2022, 2023). A method well-suited for addressing and quantifying (some of) these issues is environmental Life Cycle Assessment (LCA) (ISO, 2006b, 2006a; Hauschild, Rosenbaum and Irving Olsen, 2018). A relatively wide body of CDR-related LCA literature exists, mostly addressing Direct Air Carbon Capture and Storage (DACCS), biochar applications, and bioenergy with Carbon Capture and Storage (BECCS). However, the quality of a large fraction of available LCA literature is questionable, results might thus not be reliable, and the relevance from a Swiss perspective is often limited – due to inconsistent approaches, arbitrary assumptions, geographical variability and lack of empirical data (Goglio *et al.*, 2020; Brander *et al.*, 2021; Terlouw, Bauer, *et al.*, 2021; Butnar *et al.*, 2024). Moreover, representative, publicly accessible and transparent Life Cycle Inventories (LCI) are missing for most CDR options.

The issues of net-effectiveness and permanence of CO_2 removal – key factors in any CDR-related LCA – are also relevant in the context of certification schemes of CDR methods, including monitoring, reporting and verification (MRV). The speed and lack of oversight with which the certification landscape for CDR is evolving is posing a challenge, as there is a lack of consistency, transparency, and clarity (Arcusa and Sprenkle-Hyppolite, 2022). Markets for carbon removals must not risk their credibility in the same way as carbon offset markets recently did (Allen *et al.*, 2020; Gifford, 2020; West *et al.*, 2020; Calel *et al.*, 2021; Kreibich and Hermwille, 2021; Watt, 2021; Badgley *et al.*, 2022; Probst *et al.*, 2024) and therefore, an accurate and reliable certification scheme is essential for the scale-up of CDR – CDR providers, credit buyers, and policy makers all rely on certification to assess, incentivize, and purchase or sell CDR credits or services (Cox and Edwards, 2019; Arcusa and Sprenkle-Hyppolite, 2022). A comprehensive evaluation of CDR certification schemes is not available today and CDR certification in general would profit from learnings from the LCA perspective.

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[13] Also often referred to as «Negative Emission Technologies – NET».

To close some of these knowledge and research gaps, to quantify net-effectiveness and permanence of CO_2 removal, and to contribute to a better understanding of the broader environmental perspective of various CDR options in the context of the Swiss net zero GHG emission goal, the Swiss Federal Office for the Environment (FOEN) has commissioned this study carried out by the Technology Assessment group at PSI and the Sustainability in Business Lab at ETHZ.

1.2 Goal and scope

The activities and outcomes of this project aim at closing some of the above-mentioned knowledge gaps. The project goals can be summarized as follows:

1. Provide an overview of CDR basics summarizing state-of-the-art knowledge
2. Quantify the long-term carbon removal effectiveness of a range of CDR options from a life-cycle perspective in a parameterized setting under current boundary conditions.
3. Identify key drivers regarding carbon removal effectiveness.
4. Identify preferred CDR options from the environmental perspective based on comparative LCA with net-carbon removal effectiveness as main criterion.
5. Provide transparent and open-access life cycle inventories for these CDR options.
6. Contribute to the establishment of CDR in practice by designing a “screening LCA tool”, which will facilitate a market entry of CDR start-ups.
7. Provide an overview and a discussion of most relevant directions of future research and development in the CDR context from a Swiss perspective.

This work complements past and ongoing CDR related projects on behalf of the Federal administration. Overall, the activities will provide decision support and scientific evidence for the Swiss Federal administration, which is urgently needed in the quickly developing area of CDR as not to delay its application any further and avoid negative effects of such delay (Galán-Martín *et al.*, 2021). In addition, the project will contribute to strengthening the scientific expertise in Switzerland in the context of CDR.

In terms of specific CDR methods, the scope of the work includes the following:

- Direct Air Carbon Capture and Storage (DACCS)
- Biochar – focusing on biochar-to-soil applications
- Bioenergy with Carbon Capture and Storage (BECCS) – focusing on wood and municipal waste combustion with carbon capture and storage (CCS)
- Enhanced weathering of rocks
- Ocean liming
- Long-term storage of carbon in the construction sector, which represents a form of Carbon Capture and Utilization (CCU) – focusing on storing biogenic CO_2 in recycled concrete aggregates and using wood as construction material (qualitative discussion only)

This focus is mainly motivated by the relevance of these CDR methods from a Swiss perspective, regarding both the domestic applicability of these CDR methods and the fact that relevant actors in the context of these CDR methods are located and/or operating in Switzerland.

Further, an “LCA tool” is provided[14], which contains parameterized LCA data for several CDR options and allows for a quantification of net effectiveness of CDR as function of life cycle GHG emissions under various boundary conditions (for example, country of application, climate conditions, CO_2 transport distances, etc.), depending on the specific CDR option in focus. This tool is specifically designed to explore the CDR options with parameter settings with a broad scope beyond Switzerland. Characterization of CDR methods represents technologies as of today based on the currently available

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[14] https://www.psi.ch/de/ta/tools and https://www.suslab.ch/projects-1/life-cycle-assessment-of-carbon-dioxide-removal-options

knowledge. We assume that CDR options would be implemented and operated today, even if their development stage differs and practical implementation is likely to take place only in a few years from now. Prospective LCA – i.e., modifying both foreground and background inventory data is beyond the scope of this analysis.

2 CDR basics: methods, definitions, terminology, and current status

According to the IPCC, "CDR refers to anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological, geochemical, or chemical CO_2 sinks, but excludes natural CO_2 uptake not directly caused by human activities. Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) applied to fossil CO_2 do not count as removal technologies. CCS and CCU can only be part of CDR methods if the CO_2 is biogenic or directly captured from ambient air, and stored durably in geological reservoirs or products." (IPCC, 2022b).

This definition is applied throughout this work and report.

In general, the scientific community agrees on the fact that limiting global warming well below two degrees requires net-zero CO_2 emissions around 2050 (IPCC, 2022b; Smith *et al.*, 2023). The term "net-zero" refers to the fact that some GHG emissions – e.g., from agriculture, aviation, industrial process emissions, etc. – cannot entirely be eliminated; these emissions must be compensated for by removal of CO_2 (or other GHG) from the atmosphere (Figure 2.1) (Smith, 2021). The extent to which CDR will be needed to reach net-zero depends on several factors such as economic development, population growth, future energy demand, levels and timing of GHG emission reductions, and peak temperatures (Strefler *et al.*, 2018; Van Vuuren *et al.*, 2018; Rogelj *et al.*, 2019; IEA, 2021; IPCC, 2022b; Smith *et al.*, 2023; Edelenbosch *et al.*, 2024). Expected amounts required are in the gigatons per year range.

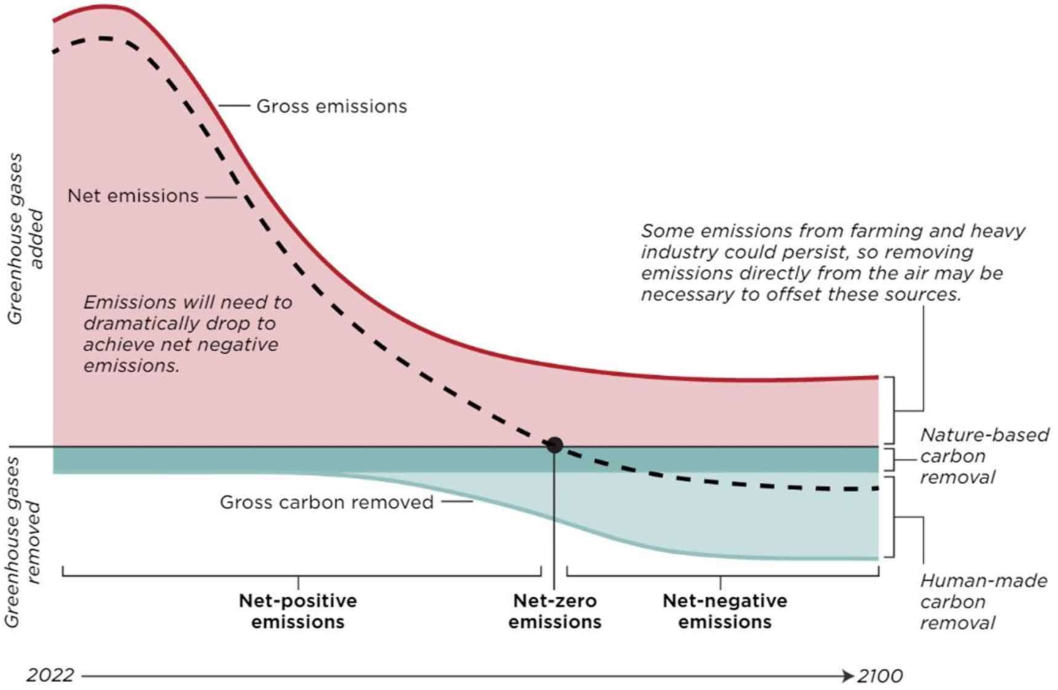

Figure 2.1: Stylized visualization of GHG emissions pathways to limit global warming well below 2 degrees and the net-zero concept (Sovacool et al., 2022).

Overall, from an international perspective, there are three roles for CDR to play in the future, each with its own temporal perspective (IPCC, 2022b):

1) Near-term: accelerating ad adding to mitigation efforts
2) Mid-term: counterbalancing hard-to-abate or left-over emissions
3) Long-term: achieving net-negative emissions

From the current Swiss perspective, counterbalancing residual greenhouse gas emissions from hard-to-abate sectors like agriculture, aviation and industry represents the focus of CDR applications.[15]

Current climate mitigation scenarios limiting global warming at 2 degrees and below – be it on the global or European level – basically all rely on large-scale implementation of CDR (Figure 2.2)[16]. CDR employment levels mainly depend on the level of temperature increase in those scenarios, future reductions of GHG emissions and socio-economic developments (Boitier *et al.*, 2023; Smith *et al.*, 2023).

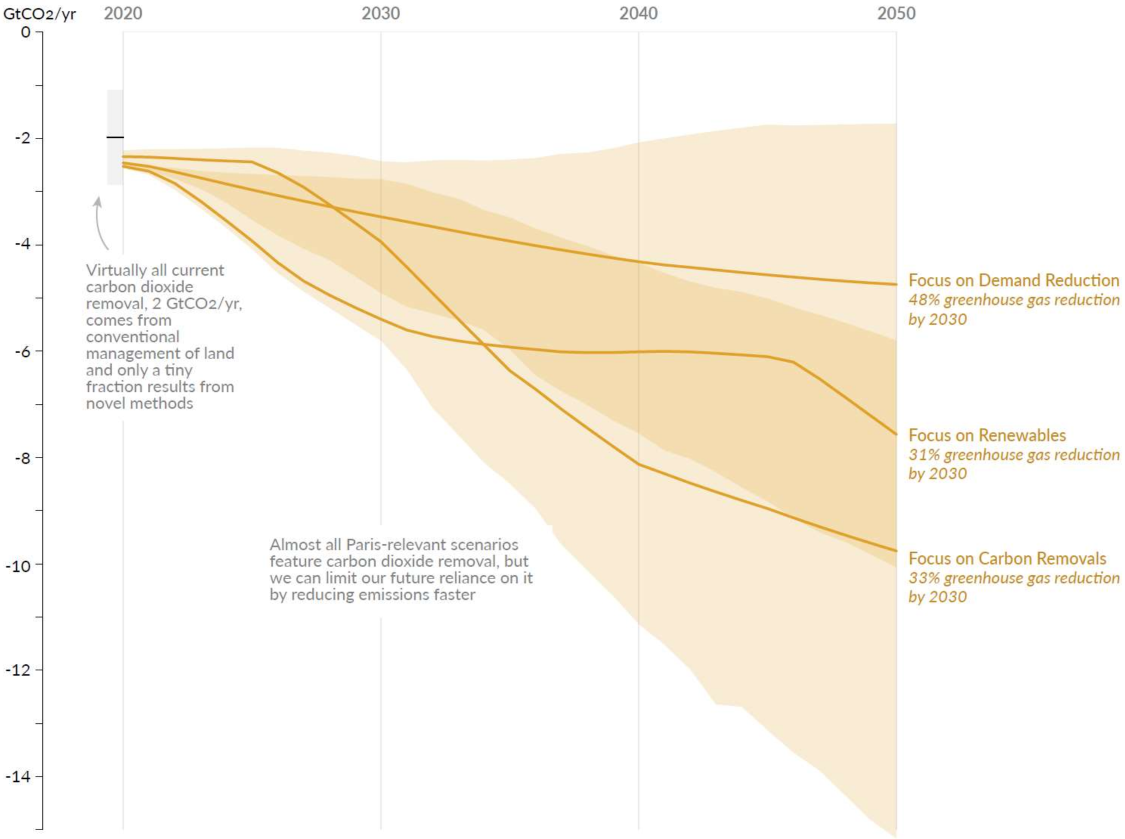

Figure 2.2: Levels of global carbon dioxide removal (Gt CO_2/a), in 2020 and in three illustrative scenarios consistent with the Paris agreement limiting global warming "well below two degrees" (Smith et al., 2023).

Comparing the amounts of CDR needed[17] in such "Paris compatible" scenarios with what has been announced on national levels or is part of national mitigation strategies, results in considerable "CDR gaps", as there are currently few plans by countries to scale CDR above current levels, exposing a substantial shortfall (Smith *et al.*, 2023; Lamb *et al.*, 2024). However, delaying CDR implementation puts climate targets at risk (Galán-Martín *et al.*, 2021; G. F. Nemet *et al.*, 2023) and fast scale-up is needed (G. Nemet *et al.*, 2023). The Swiss confederation acknowledges this perspective and specified two distinct phases for CDR development and employment: a so-called "pioneering phase" until 2030, in which first steps in terms of research, development and implementation are supposed to be taken,

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[15] https://www.bafu.admin.ch/bafu/de/home/themen/klima/dossiers/magazin-2022-2-dossier/negativemissionstechnologien-notwendiges-standbein-der-klimapolitik.html (30.11.2023).

[16] It is worthwhile noting in this context that the vast majority of such mitigation scenarios builds upon the assumption of continued economic growth (Ampah *et al.*, 2023).

[17] To put this "Several gigatons of CO_2" to be removed by CDR into perspective: Today, fossil fuel combustion and land use changes add ca. 41 Gt of CO_2 per year to the atmosphere. This additional CO_2 is partially entering carbon stocks in oceans and biomass, but a net gain of 19 Gt CO_2 per year remains in the atmosphere (The Economist, 2023).

and a dedicated scale-up phase after 2030, which includes also the implementation of the required large-scale infrastructure for both CCS and CDR, domestically and abroad (Der Bundesrat, 2022).

2.1 Options and methods for CO_2 removal

CDR methods are often distinguished based on whether they are "technical" or "nature-based". However, the IPCC notes that this frequently cited "nature vs. technology" categorisation is not a valuable distinction. They instead categorise based on the removal process:

- land-based biological
- ocean-based biological
- geochemical
- chemical

Figure 2.3 provides a schematic overview of this categorization including the timescale of CO_2 storage.

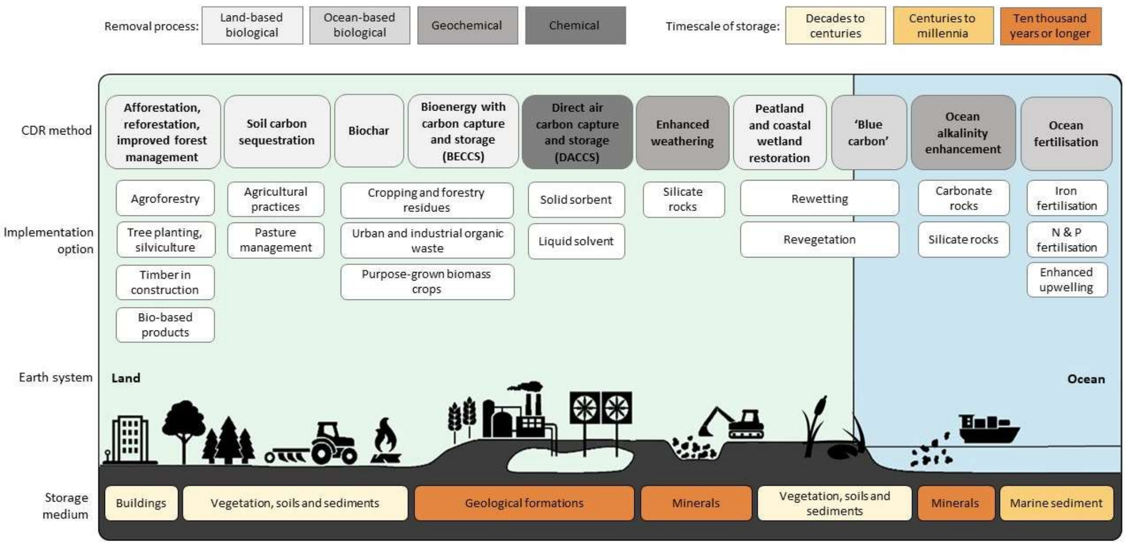

Figure 2.3: Schematic overview of CDR options according to (IPCC, 2022a).[18]

Other categorization schemes exist, for example as proposed by (Cobo *et al.*, 2023). They differentiate between terrestrial, marine, and chemical CDR methods, and BECCS (Figure 2.4).

Today, virtually all deployed CO_2 removal is associated with conventional management of land (or so-called "conventional"[19] CDR methods), mainly via afforestation, reforestation and management of existing forests (Smith *et al.*, 2023). Among the "novel"[20] CDR methods, BECCS dominates, and biochar applications are also already in place (Figure 2.5).

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[18] Figure taken from https://evetamme.com/2022/04/06/ar6-wgiii-report-carbon-removal/ (19.11.2022)

[19] "Methods that both capture and store carbon in the land reservoir. They are well-established practices already deployed at scale (TRL 8-9) and widely reported by countries as part of their Land Use, Land Use Change and Forestry (LULUCF) activities." (Smith *et al.*, 2023).

[20] "All other methods, storing captured carbon in the lithosphere (geological formations), ocean or products. Generally at a TRL below 8-9, these methods are currently deployed at smaller scales." (Smith *et al.*, 2023).

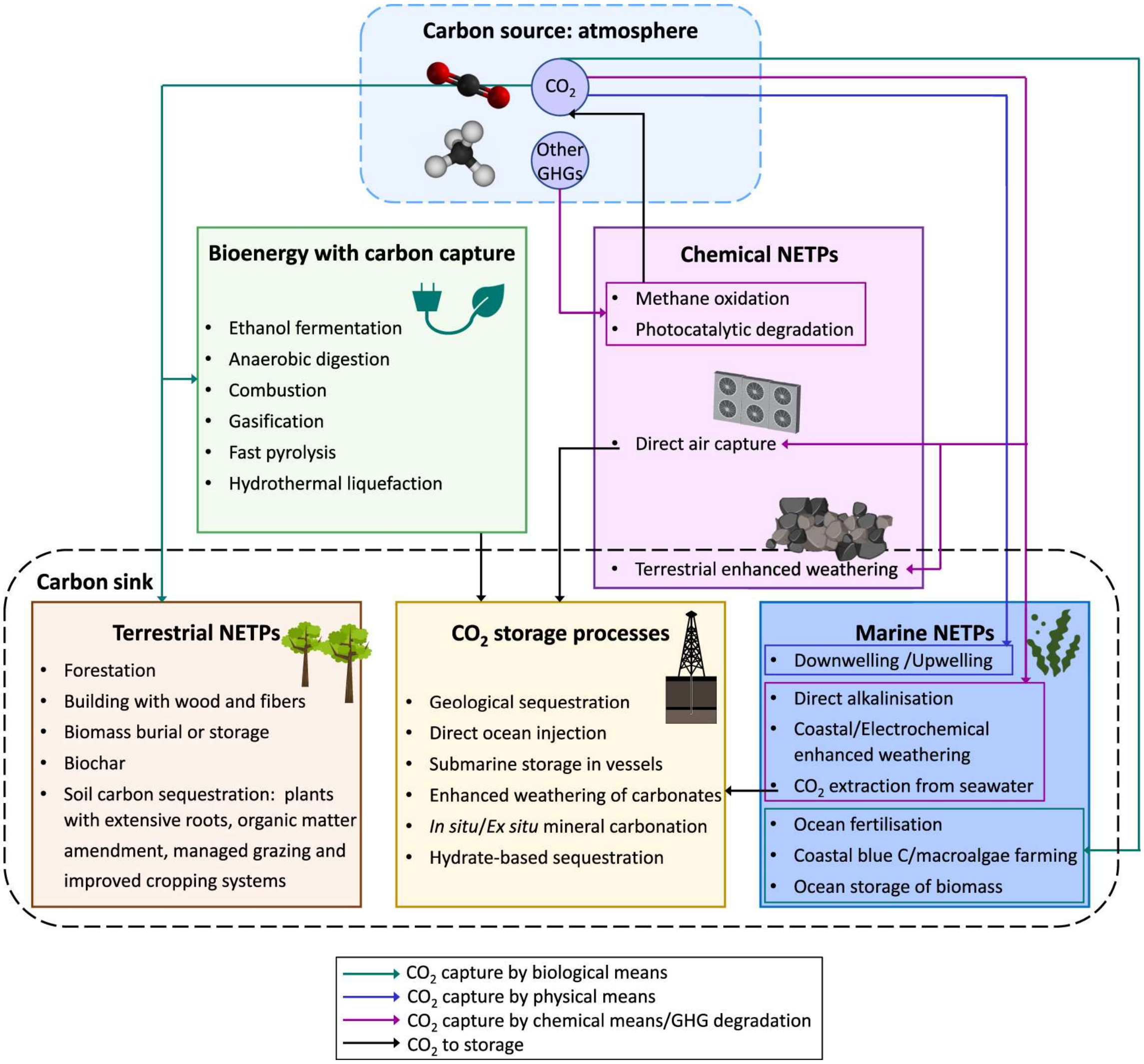

Figure 2.4: Overview and categorization of CDR methods and CO_2 sequestration processes according to (Cobo *et al.*, 2023).

Substantially increasing CDR employment would correspond to scaling up novel CDR methods, as maintaining or even slightly increasing conventional CDR on land by 2030, as planned by many countries and economic regions like the European Union, is a huge challenge on its own requiring dedicated policies and management (Doelman *et al.*, 2020; Cobo *et al.*, 2023; Gidden *et al.*, 2023; Smith *et al.*, 2023; Ganti *et al.*, 2024; Koponen *et al.*, 2024; Zhao *et al.*, 2024). Further, there are major uncertainties regarding incomplete GHG emission measurements and accounting related to such nature-based climate change mitigation and CDR methods (Buma *et al.*, 2024). Substantial demand for upscaling novel CDR methods is in contradiction with most of the long-term Low Emission Development Strategies submitted to the United Nations Framework Convention on Climate Change (UNFCCC), which mostly rely on forests and soils to reach net-zero (Smith, Vaughan and Forster, 2022).

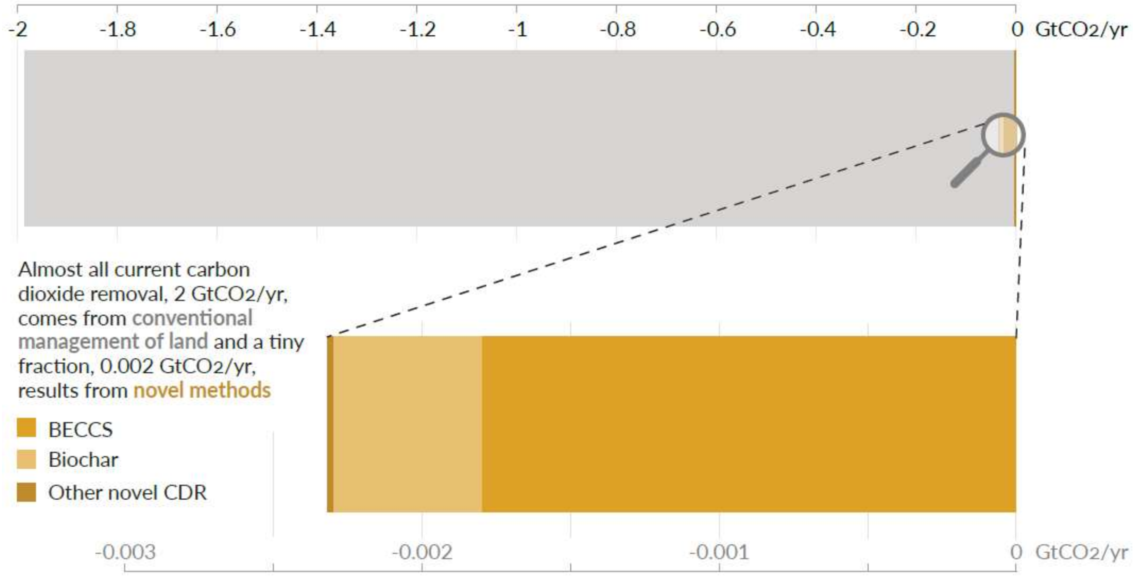

Figure 2.5: Total current amount of carbon dioxide removal, split into conventional (top, in grey: afforestation, reforestation and management of existing forests) and novel (bottom, orange: BECCS, DACCS, biochar, etc.) CDR methods (Gt CO_2/a) (Smith et al., 2023).

2.2 Basic characterization of CDR methods

Table 2.1 provides a broad overview of CDR methods according to the latest IPCC assessment, including technology readiness level (TRL[21]), estimated costs and potentials for CO_2 removal, risks, co-benefits and potential trade-offs (IPCC, 2022a). Very recently, (Prütz *et al.*, 2024) provided a comprehensive overview and a taxonomy on co-benefits, challenges and limits of CDR.

From today's Swiss perspective, most relevant CDR methods are BECCS (with a focus on waste-to-energy plants with CCS) and DACCS (likely to be implemented abroad) (Der Bundesrat, 2022). Further CDR methods to be considered as potential domestic contributors to reach net zero GHG emissions are land-based and include forest-related methods, storage of CO_2 in recycled concrete aggregates, long-term carbon capture and utilization – e.g., using wood as construction material –, soil carbon sequestration (SCS), biochar applications, bioenergy (including municipal solid waste incineration) with CCS, DACCS, enhanced weathering (EW) and peatland restoration. However, this focus might change in the future, as CDR potentials within the Swiss borders seem to be limited and not match overall CDR needs to reach Swiss net-zero goals and CDR application abroad might be more cost-efficient or beneficial from an environmental perspective (Kirchner *et al.*, 2020; Kemmler *et al.*, 2021; Brunner and Knutti, 2022; Der Bundesrat, 2022; Panos, Ramachandran, *et al.*, 2023). Especially ocean-based CDR methods promise large CDR potentials. At the same time, however, large uncertainties exist whether these can keep their promises (Jeltsch-Thömmes *et al.*, 2024; Roman Nuterman and Markus Jochum, 2024; Yamamoto, DeVries and Siegel, 2024).

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[21] A definition of technology readiness levels is provided for example here: https://en.wikipedia.org/wiki/Technology_readiness_level (18.3.2024).

Table 2.1: Overview of CDR options, their TRL, costs, potentials, risks, co-benefits, and trade-offs from a global perspective (modified, after (IPCC, 2022a)). Impacts, co-benefits, and trade-offs, which can be addressed by LCA in *italics*. Not all issues listed here might be relevant in a Swiss context, especially for CDR methods with critical site-specific characteristics and impacts.

CDR option	Status (TRL)	Cost (at scale) (USD/tCO_2)	Mitigation potential (Gt CO_2/year)	Risks/impacts	Co-benefits	Trade-offs, spill over events
Ocean Alkalinity Enhancement	1-2	40-260	1-100	Increased seawater pH and saturation states may impact marine biota. Possible *release of toxic elements*. *Mining impacts*.	Limit ocean acidification.	*Potentially increased emissions of CO_2 and dust from mining, transport and deployment operations*.
Ocean fertilisation	1-2	50-500	1-3	Nutrient redistribution, restructuring of the ecosystem, enhanced oxygen consumption and acidification in deeper waters, potential for decadal-to-millennial-scale return to the atmosphere of nearly all the extra carbon removed, risks of unintended side effects.	Increased productivity and fisheries, reduced upper ocean acidification.	Subsurface ocean acidification, deoxygenation; altered meridional supply of macronutrients as they are utilized in the iron fertilized region and become unavailable, fundamental alteration of food webs, biodiversity.
Blue carbon	2-3	Insufficient data	<1	If degraded or lost, coastal blue carbon ecosystems are likely to release most of their carbon back to the atmosphere; potential for sediment contaminants, toxicity, bio-accumulation and -magnification in organisms; issues related to altering degradability of coastal plants; use of subtidal areas for tidal wetland carbon removal; effect of shoreline modifications on sediment redeposition and natural marsh accretion; abusive use of coastal blue carbon as means to reclaim land for purposes that degrade capacity for CDR.		Provide many non-climatic benefits and can contribute to ecosystem-based adaptation, coastal protection, increased biodiversity, reduced upper ocean acidification; could potentially benefit human nutrition or produce fertiliser for terrestrial agriculture, anti-methanogenic feed additive, or as an industrial or materials feedstock.
Enhanced Weathering	3-4	50-200	2-4	*Mining impacts*, *air quality impacts* of rock dust on soils.	Enhanced plant growth, reduced erosion, *increased (inorganic) soil carbon*, reduced pH, soil water retention.	*Potentially increased GHG and pollutant emissions from water supply and energy generation*.
DACCS	6	100-300	5-40	*Increased energy and water use*.	*Water produced* (solid sorbent only).	*Increased emissions from water supply and energy generation.*

CDR option	Status (TRL)	Cost (at scale) (USD/tCO_2)	Mitigation potential (Gt CO_2/year)	Risks/impacts	Co-benefits	Trade-offs, spill over events
BECCS	5-6	15-400	0.5-11	*Competition for land and water resources*, to grow biomass feedstock. Biodiversity and *carbon stock loss,* if from unsustainable biomass harvest. *Potentially reduced nutrient availability and soil organic carbon* due to biomass use.	*Reduction of air pollutants*; fuel security, optimal use of residues, additional income, health benefits and if implemented well can enhance biodiversity, soil health and land carbon.	Competition for land with biodiversity conservation and food production.
Biochar	6-7	10-345	0.3-6.6	*Particulate and GHG emissions from production*; biodiversity and carbon stock loss from unsustainable biomass harvest.	*Increased crop yields and reduced non-CO_2 emissions from soil (depending on properties of agricultural soils)*; and resilience to drought.	*Environmental impacts associated particulate matter; competition for biomass resource*.
Afforestation/ Reforestation	8-9	0-240	0.5-10	Reversal of carbon removal through wildfire, disease, pests may occur. Reduced catchment water yield and lower groundwater level if species and biome are inappropriate.	Enhanced employment, improved biodiversity, *improved renewable wood products provision*, *soil carbon* and nutrient cycling. Possibly less pressure on primary forest.	Inappropriate deployment at large scale can lead to *competition for land* with biodiversity conservation and food production.
Soil carbon in crops and grassland	8-9	45-100	0.6-9.3	Risk of increased *nitrous oxide emissions* due to higher levels of organic nitrogen in the soil; risk of reversal of carbon sequestration.	*Improved* soil quality, resilience, and *agricultural productivity*.	Attempts to increase carbon sequestration potential at the expense of production. Net addition per hectare is very small; hard to monitor.
Peatland and coastal wetland restoration	8-9		0.5-2.1	Reversal of carbon removal in drought or future disturbance. Risk of *increased methane emissions*.	Enhanced employment and local livelihoods, increased productivity of fisheries, improved biodiversity, soil carbon and nutrient cycling.	*Competition for land* for food production on some peatlands used for food production.
Agroforestry	8-9		0.3-9.4	Risk that some land area lost from food production; requires high skills.	Enhanced employment and local livelihoods, variety of products improved soil quality, more resilient systems.	Some trade-offs with agricultural crop production, but enhanced biodiversity, and resilience of system.
Improved forest management	8-9		0.1-2.1	If improved management is understood as merely intensification involving increased fertiliser use and introduced species, then it could reduce biodiversity and increase eutrophication.	In case of sustainable forest management, it leads to enhanced employment and local livelihoods, enhanced biodiversity, improved productivity.	If it involves increased fertiliser use and introduced species, it could reduce biodiversity and increase eutrophication and upstream GHG emissions.

CDR-specific costs and removal potentials on the global level and according to (IPCC, 2022a) are subject to large ranges, indicating substantial uncertainties, especially for CDR methods at low technology readiness levels. Those ranges, however, also indicate that for example costs can be subject to large regional variations.

A global review of CDR methods including their technical maturity, costs, CO_2 removal potentials, resource use and a qualitative assessment of potential side-effects has also been provided recently by (Cobo *et al.*, 2023). They identified trade-offs between all CDR methods, supporting the thesis that a portfolio of CDR methods will likely be needed, but at the same time categorize a few as most promising: forestation, soil carbon sequestration (SCS), enhanced weathering with olivine and three modalities of direct air carbon capture and storage (DACCS). They suggest that bioenergy with carbon capture and storage (BECCS), especially if using dedicated crops, and marine CDR methods – the latter showing imminent development levels – should not be prioritized over potentially more promising alternatives.

Recently, (Brunner and Knutti, 2022) evaluated potentials and costs of various CDR methods – namely afforestation, reforestation and improved forest management, bioenergy with carbon capture and storage, soil carbon sequestration, sequestration of biochar, enhanced silicate rock weathering, and direct air capture and storage – from a Swiss perspective – and concluded that “environmental and economic constraints do not fundamentally query a substantial contribution of CDR within Switzerland to achieving the net zero target” (Brunner and Knutti, 2022). Largest technical CDR potentials in the order of 30 Mt CO_2eq per year are available for afforestation, reforestation, and improved forest management, BECCS, and enhanced rock weathering. However, they also state that “due to several limiting factors, the actual achievable potential for CDR in Switzerland is likely to be significantly smaller than the technical potential” (Brunner and Knutti, 2022).

The following sub-sections touch upon those CDR methods, which are in focus of this work.

2.2.1 Direct Air Carbon Capture and Storage (DACCS)

Direct Air Carbon Capture and Storage is a process chain, which captures CO_2 from the ambient air and permanently stores it, typically in geological reservoirs (National Academies of Sciences Engineering and Medicine, 2019; Chauvy and Dubois, 2022). CO_2 captured through direct air capture can also be used or stored in products, in which case it is commonly referred to as Carbon Capture and Use (section 2.2.5).

Key process of this chain is the Direct Air Capture (DAC) process, which is technologically challenging due to the low CO_2 concentration in ambient air. Several options exist, which can be categorized according to four main CO_2 separation mechanisms: physical and/or chemical binding to either (i) a liquid or (ii) a solid material; (iii) separation based on differences in gas diffusivities; and (iv) separation by differences in freezing point (Küng *et al.*, 2023) (Figure 2.6). A similar categorization is proposed by (Bouaboula *et al.*, 2024).

DAC technologies that bind CO_2 to a liquid or to a solid material can be further categorized by their respective CO_2 regeneration driver (i.e., the driver that releases the CO_2 from the material it is bound to). Similarly, the separation by differences in diffusivity can be distinguished between pressure-driven processes (membrane as a sieve) and voltage-driven processes (electrochemical separation) (Küng *et al.*, 2023). The CO_2 capture material allows further differentiation. Table 2.2 provides an overview of this type of DAC process categorization, including DAC companies currently using one of these approaches.

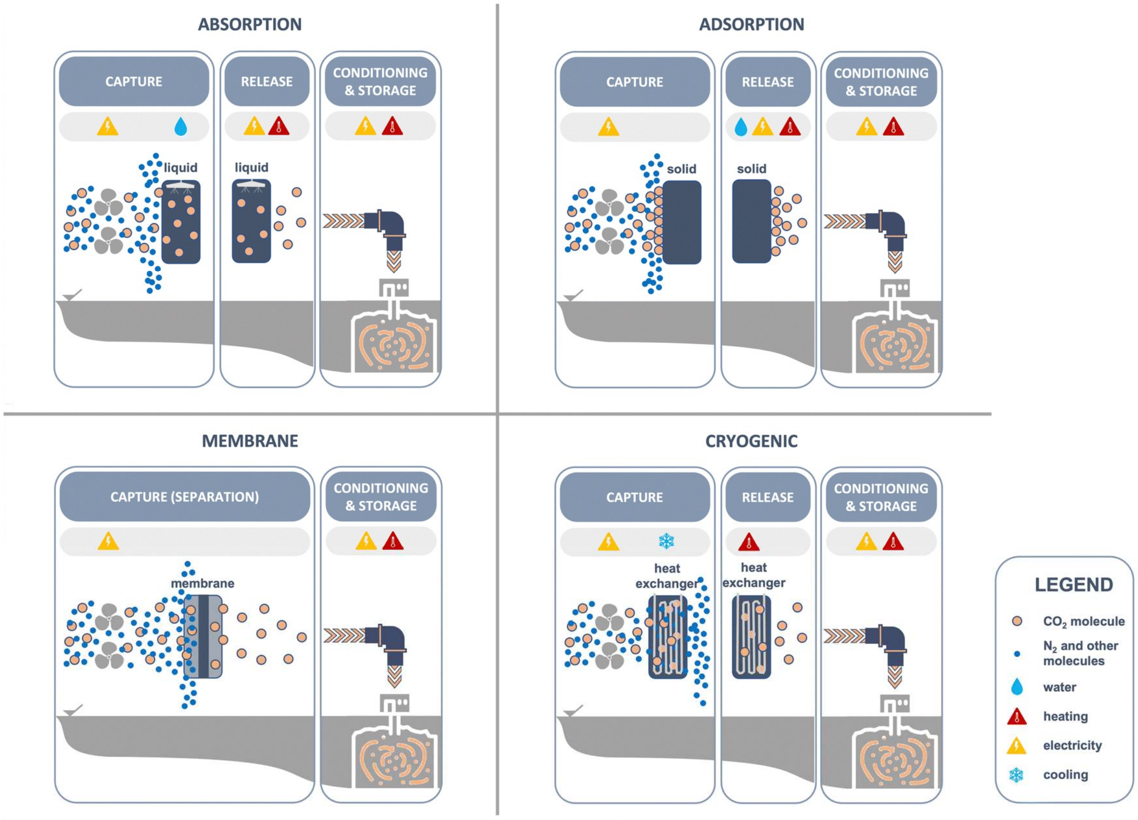


Figure 2.6: The four primary separation mechanisms in DAC processes. (i) 'Absorption', which works by binding the CO$_2$ within a liquid; (ii) 'Adsorption', which works by binding the CO$_2$ to the surface of a solid; (iii) 'Membrane' that separates via different diffusion abilities; and (iv) 'Cryogenic' process that de-sublimates (phase change from gas directly to solid without an intermediate liquid phase) CO$_2$ based on the higher freezing point compared to other atmospheric gasses (Küng et al., 2023).

(Küng *et al.*, 2023) provide also further information on TRL, energy, water, raw material consumption, and estimated land use for all DAC categories. In addition, they identify technology and material related obstacles for large-scale employment of DACCS and perform cost estimations for each of the main DAC categories. Similar cost estimations have been provided by (Young *et al.*, 2023; Sievert, Schmidt and Steffen, 2024). However, it should also be taken into account that DAC performance depends on the place of employment, as some performance parameters depend on temperature and humidity of the ambient air (An, Farooqui and McCoy, 2022).

The CO$_2$ capture process is followed by CO$_2$ conditioning, compression, and transport to the geological storage site, where CO$_2$ in supercritical state is injected. Small amounts of CO$_2$ are often transported by lorries, while an upscale of DACCS would most likely require CO$_2$ transport by pipeline (Eckle, Spokaite and Krueger, 2021). Appropriate geological storages include saline aquifers and depleted natural gas and reservoirs at depths below 800 meter (Ajayi, Gomes and Bera, 2019; Wei *et al.*, 2022; Askarova *et al.*, 2023). However, from a current point of view, deep uncertainties over the sustainable CO$_2$ injection rates at any given location exist and these will constrain the pace and scale of CO$_2$ capture and storage deployment (Lane, Greig and Garnett, 2021). From a current point of view, also the uncertainties regarding the potential for geological CO$_2$ storage in Switzerland are substantial. The most recent estimate is in the order of 50 Mt CO$_2$ (Diamond *et al.*, 2019). However, "several scientists have questioned the evaluation and argued that the actual storage potential may be much more significant, especially if fracture permeability can be enhanced" (Wiemer *et al.*, 2024).

In addition, CO$_2$ can be mineralized and sequestered in solid form by various techniques, i.e., ex-situ, surficial and in situ mineralization (Kelemen *et al.*, 2019). Risks involved in underground CO$_2$

sequestration include leakage of CO_2 (Gholami, Raza and Iglauer, 2021), which would compromise the CDR effect, and induced seismicity (Cheng *et al.*, 2023).

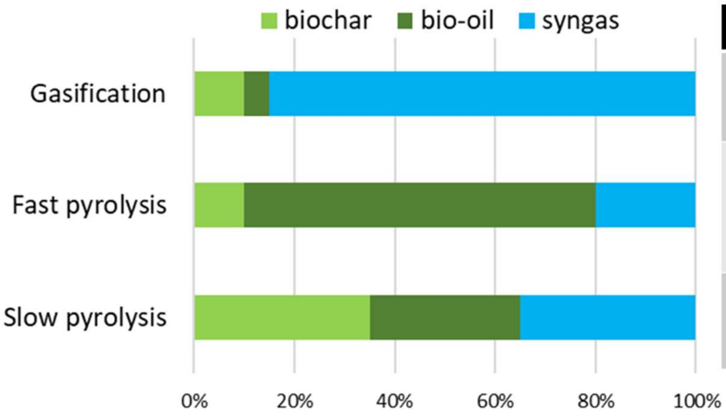
Table 2.2: Classification of DAC processes based on the CO_2 capture mechanism and release drivers (Küng *et al.*, 2023).

Capture mechanism	Release driver	Capture material	DAC Companies
1: absorption (with liquid solvent)	1A: high-grade heat	Hydroxide (KOH)	Carbon engineering[20] (1PointFive)[21]
	1B: crystallization & low-grade heat	Amino acid	—
	1C: low-grade heat stripping	Monoethanolamine (MEA)	—
		Amino acid	—
	1D: voltage	Hydroxide (KOH/NaOH)	Carbon Blade[33] CO2CirculAir (SMART-DAC)[34]
		Unknown	E-Quester[35] Mission Zero Technologies[36]
2: adsorption (with solid sorbent)	2A: high-grade heat	Hydroxide ($Ca(OH)_2$)	Heirloom,[38] Origen[39]/8 Rivers[40]
	2B: humidity	Ammonium resins	Avnos,[43] Infinitree,[44] Carbon Collect (MechanicalTrees™)[45]
		Alkali carbonate	Clairity[46]
	2C: low-grade heat and/or vacuum and/or steam	Amine[14]	Carbyon,[49] Climeworks,[18] Emissol,[50] Global Thermostat,[19] Hydrocell[51]
		MOF	Airthena™,[52] Carbon Infinity,[53] AspiraDAC[54]
		Zeolites	TerraFixing,[55] GreenCap solutions[56] (Removr[57])
		Akali carbonate	Sustaera[58] (Susteon spinout[59])
		Unknown	Air View Engineering,[60] BlancAir,[61] Carbon Capture,[62] DAC City,[63] InnoSepra,[64] Noya,[65] ReCarbn,[66] Skytree[67]
	2D: voltage	Redox-active molecule (*e.g.*, Quinone)	Verdox,[16] Holy Grail[70]
		Ion-exchange fiber	Carbominer[71]
		Hydroxide ($Ca(OH)_2$)[72]	ParallelCarbon[73]
3: membrane separation	3A: pressure gradient	Polymer membrane	—
	3B: voltage	Ion exchange membrane[75]	RepAir[76]
4: cryogenic separation	4A: phase change (vapor–solid)	N/A	HighHopes™[79]

14 (Erans *et al.*, 2022); 16 (Verdox, 2023); 18 (Climeworks, 2023); 19 (Global Thermostat, 2023); 20 (Carbon Engineering, 2023); 21 (1pointfive, 2023); 33 (Carbon Blade, 2023); 34 (CO2CirculAir, 2023); 35 (E-quester, 2023); 36 (Mission Zero Technologies, 2023); 38 (Heirloom, 2023); 39 (Origen, 2023); 40 (8 Rivers Capital, 2023); 43 (Avnos, 2023); 44 (Infinitree, 2023); 45 (Carbon Collect, 2023); 46 (Clairity Technology, 2023); 49 (Carbyon, 2023); 50 (Emissol, 2023); 51 (hydrocell, 2023); 52 (Airthena, 2023); 53 (Carbon Infinity, 2023); 54 (AspiraDAC, 2023); 55 (TerraFixing, 2023); 56 (G.Solutions, 2023); 57 (Removr, 2023); 58 (Sustaera, 2023); 59 (Susteon, 2023); 60 (Air View Engineering, 2023); 61 (BlancAir, 2023); 62 (Carbon Capture, 2023); 63 (DAC City, 2023); 64 (InnoSepra, 2023); 65 (Noya, 2023); 66 (ReCarbn, 2023); 67 (Skytree, 2023); 70 (Holy Grail, 2023); 71 (Carbominer, 2023); 72 (Parallel Carbon, 2023a); 73 (Parallel Carbon, 2023b); 75 (Rep Air, 2023); 76 (RepAir, 2023); 79 (High Hopes, 2023).

2.2.2 Biochar to soil application

Production of biochar from biomass and subsequent use as soil amendment or for other purposes (e.g., as amendment in concrete and asphalt production) can act as CDR method, as a result of the one to two orders of magnitude longer persistence of biochar than the biomass it is made from (Lehmann *et al.*, 2021; Smith *et al.*, 2023). In other words, (part of) the CO_2 taken up from the atmosphere by growing biomass is stabilized in biochar and therefore removed from the atmosphere over decades to centuries. Biomass is converted to biochar by a pyrolysis (or gasification) process, which also generates syngas and liquids (often referred to as “bio-oil”) as by-products. Highest biochar yields are achieved by the so-called "slow pyrolysis" process, which is characterized by a lack of oxygen, a slow heating rate, and a temperature in the range of 350-800°C (Hoeskuldsdottir, 2022). Alternative process options for biochar production are fast pyrolysis and biomass gasification; both are characterized by lower biochar, but higher syngas and bio-oil yields (Figure 2.7) – therefore, these processes might also be categorized as BECCS options (Cobo *et al.*, 2023) (Figure 2.9). Syngas and bio-oils are usually (partially) burned and used for energy supply of the pyrolysis process; surplus heat and/or electricity can be supplied to the market. Syngas and bio-oil combustion processes could be equipped with CCS, which would increase the CDR potential of biochar production and application.



Heating rate	Temperature	Oxygen
Moderate to very fast	700-1500°C	Limited
Very fast	350-1000°C	Absent
Slow	300-800°C	Absent

Figure 2.7: Product yields and key characteristics of biochar production processes (Hoeskuldsdottir, 2022).

In terms of biochar application, the use of biochar as soil amendment can be considered as the most frequently discussed option for CDR, even if there are many other uses such as additives in construction materials or animal feed (Schmidt, 2012; Lehmann *et al.*, 2021; Osman *et al.*, 2022; Barbhuiya, Bhusan Das and Kanavaris, 2024). Biochar-to-soil applications can come along with co-benefits such as increased crop yields, reduced CH_4 and N_2O emissions from the soil, or reduction of fertilizer requirements in agriculture. On the other hand, it might show negative impacts on soil biology, might lead to soil contamination, affect organic soil carbon, and reduce albedo effects. These effects are, however, site-specific and depend on soil characteristics, climate, etc. (Lehmann *et al.*, 2021) – thus, they need to be addressed on a case-by-case basis. In general, it can be stated that although the biochar applied to soils may release nutrients originally contained in the biomass feedstock, these are not sufficient to entirely replace conventional fertilizers (Cobo *et al.*, 2023). Further, soil types are important: while the crop yields of alkaline soils are more likely to decrease due to biochar application, the fertility and productivity of acidic soils typically improve (Tisserant and Cherubini, 2019). Biochar can adsorb nutrients and pollutants thanks to its high reactivity and specific surface area, which can contribute to soil remediation and water purification in highly contaminated sites. Also the soil's water-holding capacity can be increased (Smith *et al.*, 2019). However, adding biochar to soil might result in a reduction of the efficiency of herbicides and pesticides due to the ability of biochar to immobilize chemicals. Depending on the biomass feedstock used for biochar production, it can also be a source of contaminants, such as heavy metals, organic pollutants, particulate matter, carbon black, etc. Conversely, it can reduce nitrous oxide emissions from fertilized soils (Tisserant and Cherubini, 2019). Further, the soil application of biochar can either decrease or increase ammonia and methane emissions rates of soils, depending on the soil and biochar properties (Tisserant and Cherubini, 2019; Schmidt *et al.*, 2021).

In the Swiss context and according to (BAFU, 2023), there is so far no evidence that biochar use as agricultural soil amendment leads to increased crop yields. It is also stated that substantial carbon storage cannot be expected to go hand in hand with increased crop yields in Switzerland, as opposed to for example tropical regions, where soil characteristics are different and more favorable for such effects. One critical issue according to (BAFU, 2023) is the potentially negative and irreversible impact of biochar application on agricultural soil on soil biology. Overall, the lack of long-term, practical evidence in the field regarding both positive and negative side-effects of the use of biochar as agricultural soil amendment is stressed and thus, for the time being, large-scale application of biochar in agriculture in Switzerland is not recommended, as long as harmful impacts especially on soil biology cannot be excluded (BAFU, 2023).

In general, one of the key issues regarding the CDR potential of biochar-to-soil applications is the permanence of CO_2 removal from the atmosphere, i.e., the persistence of carbon in biochar in the soil (or other applications) (Gurwick *et al.*, 2013; Sanei *et al.*, 2024). If used in long-lived products, such as building materials, the biochar carbon sink is secure if the product is not burned. If biochar is used as soil amendment, its carbon persistence depends on its molecular composition and the soil characteristics. The molecular composition is represented by the relative amounts of carbon to hydrogen or oxygen atoms and is determined by feedstock characteristics and pyrolysis temperature (Lehmann *et al.*, 2021; Woolf *et al.*, 2021; Tisserant *et al.*, 2022) A driving soil characteristic for biochar stability is soil temperature. The so-called "carbon stability factor"[22] is thus the result of a complex interplay of many factors, but can be estimated by soil temperature and pyrolysis temperature based on empirical evidence (Woolf *et al.*, 2021), as shown in Figure 2.8.

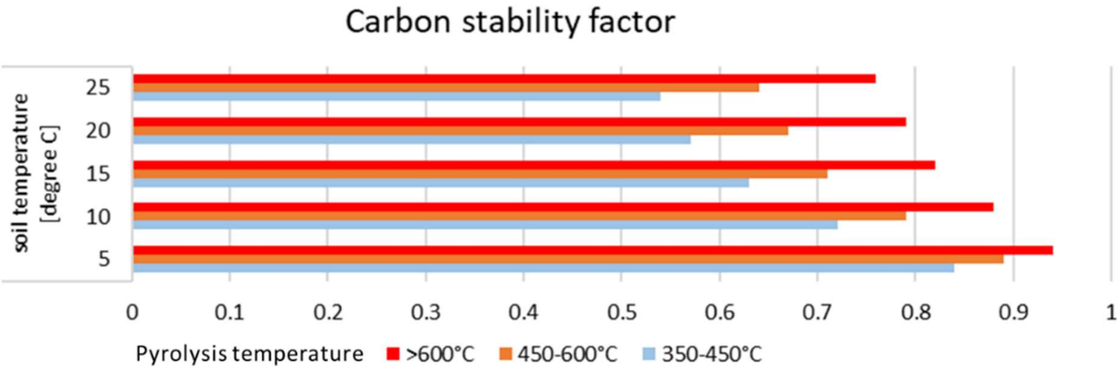


Figure 2.8: Carbon stability factor of biochar-to-soil application as a function of pyrolysis and soil temperatures (Hoeskuldsdottir, 2022) based on (Woolf *et al.*, 2021).

Within this project, we will focus on the LCA of biochar-to-soil applications. LCA of other use options, e.g., as additives in building materials or animal feeds, should be subject of further research.

2.2.3 Bioenergy with Carbon Capture and Storage (BECCS)

There is a broad variety of Bioenergy with Carbon Capture and Storage (BECCS) technology chains combining different biogenic feedstock, conversion technologies and CO_2 capture and storage options to provide heat and electricity as well as gaseous and liquid energy carriers – all of them with the potential to permanently remove CO_2 from the atmosphere (Kemper, 2015; Fajardy and Mac Dowell, 2017; Bui *et al.*, 2018; Pour, Webley and Cook, 2018; Negri *et al.*, 2021; Rosa, Sanchez and Mazzotti, 2021; Shahbaz *et al.*, 2021; Paulillo *et al.*, 2024). All BECCS methods are based on the principle to capture carbon released during biomass conversions as CO_2, which was removed from the atmosphere during photosynthesis, and subsequently permanently sequester it.

(Cobo *et al.*, 2023) categorize BECCS process chains as shown in Figure 2.9. They differentiate between biological and thermochemical processes to turn biomass into energy vectors such as heat and electricity, liquid and gaseous hydrocarbons, and also hydrogen. In general, the effectiveness of BECCS

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[22] Equivalent to the fraction of carbon stored in soil after 100 years relative to the original carbon content of biochar applied at time of application.

process chains in removing CO_2 from the atmosphere largely depends on the type of biomass used, its biogenic carbon content, and the capture rate.

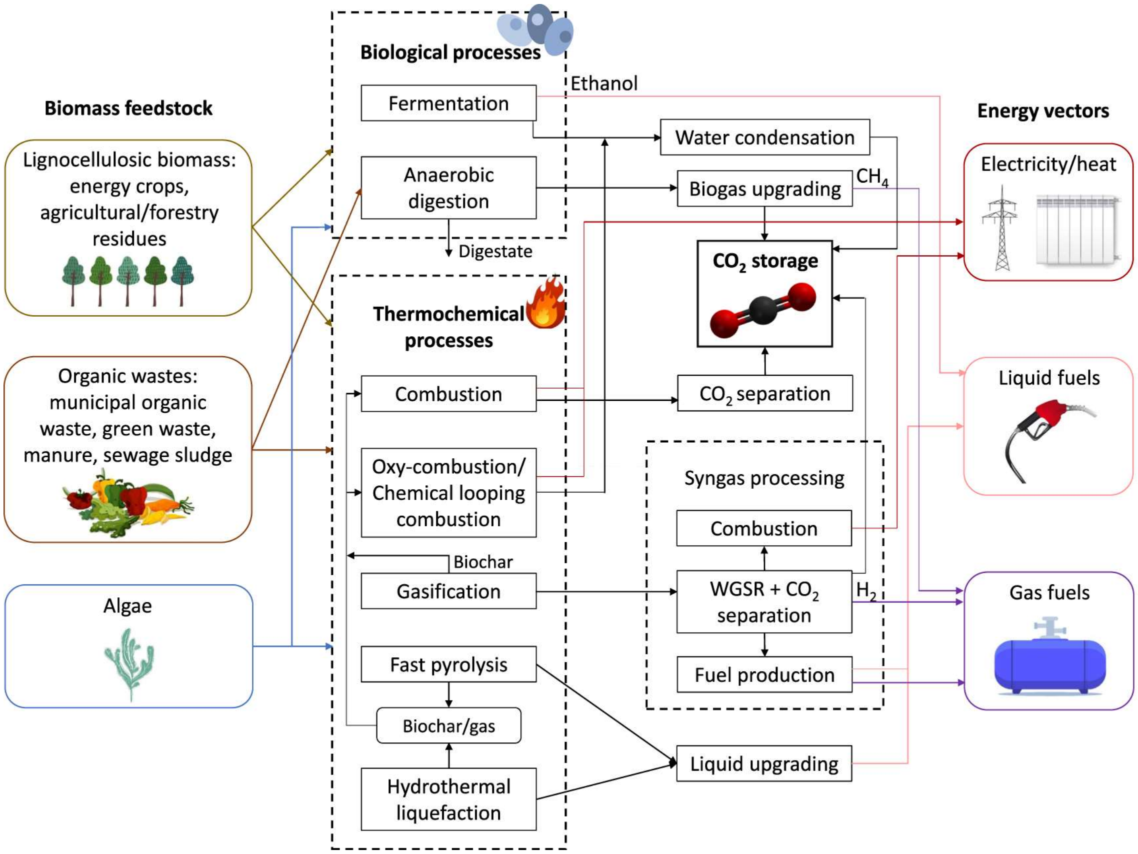

Figure 2.9: BECCS configurations and categorizations according to (Cobo et al., 2023). Note that "biochar" can be considered as BECCS option, but also as a CDR method on its own, mostly depending on whether biochar production and application is the main purpose of the process chain, or energy vector production with biochar as a by-product.[23]

Biomass can be sourced from agricultural and forest residues, but the overall sustainable CDR potential of this type of feedstock is limited because of their important role in maintaining soil fertility and soil organic carbon stocks (Smith *et al.*, 2015). Also, the energy valorization of organic wastes coupled with CCS can represent CDR opportunities (Feng and Rosa, 2024). Perennial energy crops including grasses such as switchgrass and miscanthus, and short-rotation coppice like poplar are particularly promising feedstocks because of their high yields, ability to grow on marginal land and potential contribution to soil carbon sequestration (Cobo *et al.*, 2023). The cultivation of dedicated bioenergy crops in agricultural and forested lands could interfere with the global food supply and biodiversity conservation (Smith *et al.*, 2015). Thus, BECCS is primarily constrained by land availability, crop productivity, and the available amounts of residual biomass.

Overall, the CDR potential of BECCS shows high regional variability and strongly depends on the biomass cultivation location with higher CDR rates achievable in subtropical and warm temperate areas, where biomass yields are usually high and initial land use change emissions low (Hanssen *et al.*, 2020). Nevertheless, any loss in soil carbon induced by land use change could offset the sequestered CO_2 under non-optimal conditions (Fajardy and Mac Dowell, 2017). Regarding other climate impacts

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[23] Biochar can be produced via gasification, slow and fast pyrolysis of biomass. If biochar production is the main purpose, slow pyrolysis is the process of choice, as it shows the highest biochar yield (see Figure 2.7 in section 2.2.2). If liquid and gaseous energy carrier production is the main purpose, gasification and fast pyrolysis are the processes of choice, as indicated in (Figure 2.9).

of BECCS, it is commonly assumed that a decrease in the surface albedo associated with biomass plantations may further reduce the climate benefits, although (Wang *et al.*, 2021) recently indicated that bioenergy crops could induce a global cooling effect. Some of the side-effects of land-based BECCS could be avoided or at least reduced by using cultivated algae as biomass feedstock – at increasing costs, however. In general, algae-based BECCS systems cannot be considered as well understood, as impacts on marine ecosystems are largely unknown and net effects on CDR due to drying and transport of feedstock poorly quantified (Cobo *et al.*, 2023).

From a Swiss perspective, most relevant biogenic feedstocks, which can be combined with CCS, are woody biomass, manure, and the biogenic fraction of the municipal waste. Wood combustion plants generating heat and electricity can be equipped with CCS; wood can also be gasified to produce hydrogen and the gasification can be combined with CCS; manure can be converted to biomethane, which can further be converted to hydrogen and the methane reforming can be combined with CCS; municipal waste incineration can be equipped with CCS and the combustion of the biogenic waste fraction with CO_2 capture and subsequent CO_2 transport and storage can be considered as BECCS. These BECCS options most relevant for Switzerland can be considered as sustainable as they can be expected not to be associated with negative side effects in terms of competing with agriculture for land and thus food production and in terms of induced land use changes – as long as only residual biomass streams and no dedicated crops and only sustainably harvested wood would be used, which seems to be very likely (Brunner and Knutti, 2022; Der Bundesrat, 2022).

2.2.4 Enhanced Weathering (EW) of rocks

Rock weathering is a natural process, part of the earth's natural carbon cycle, where rocks undergo physical, chemical, or biological changes over geological time scales (Bland and Rolls, 1995). Physical or mechanical weathering happens when the rock is broken down into smaller fragments without chemical altering. For example, when temperatures decrease, the water absorbed from rocks turns into ice. When the water turns into ice, its volume increases, expanding and pressuring the rock from the inside out, resulting in a broken rock. Chemical weathering happens when the minerals in the rocks are changed by encountering water, oxygen, carbon, or other organic acids. For example, when carbon dioxide dissolves in rainwater to form carbonic acid, it reacts with calcite or calcium carbonate in limestone and forms calcium bicarbonate, which can be dissolved in water. In this way, this process breaks down the limestone and consumes carbon dioxide from the atmosphere (Bland and Rolls, 1995). Examples of biological weathering would be when tree roots break a specific part of the earth's surface or when algae and fungi chemically alter the minerals in rocks, they grow close to. The organic acids released as a byproduct of their metabolic processes react with the minerals by consuming carbon dioxide, weakening the rock, which leads to its physical breakdown.

Enhanced Rock Weathering (ERW), often referred to as simply Enhanced Weathering (EW), is a CDR method based on amending soils with crushed calcium- and magnesium-rich silicate rocks to accelerate CO_2 sequestration (Beerling *et al.*, 2020). The silicate rock grains chemically react with CO_2 to form bicarbonate dissolved ions[24] (Lefebvre *et al.*, 2019):

$$CaSiO_3 + 2CO_2 + 2H_2O \rightarrow Ca^{2+} + 2HCO^{-}_{3\,(to\ Ocean)} + SiO_2 + H_2O$$

These are transported by rivers to the oceans and potentially stored for hundreds of years and longer, depending on calcium carbonate sedimentation processes (Goll *et al.*, 2021). However, when soil conditions are favorable, some of the calcium and magnesium cations can precipitate to form carbonate minerals (Lefebvre *et al.*, 2019):

$$\boldsymbol{Ca}^{2+} + 2\,\boldsymbol{HCO}_3^{-} \leftrightarrow CaCO_{3(\ in\ soils)} + CO_2 + H_2O$$

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[24] Shown here for wollastonite as example.

This process – referred to as carbonation – accounts for half the moles of CO_2 captured during the weathering of the rock. The capture potential of each path (i.e. Carbonation and EW) depends on the type of rock used (Lefebvre *et al.*, 2019).

Different types of rocks, such as glauconite, basalt, serpentine, olivine, limestone, and dolomite, are used for EW. Some types show quicker dissolution and CO_2 absorption rates than others. For example, olivine and glauconite have shown faster CO_2 capture/sequestration rates, while serpentine, limestone, and basalt offer slower weathering and CO_2 sequestration rates (AgriTech Verde, 2023). Beside silicate rocks, carbonate minerals (e.g., calcite, $CaCO_3$) could provide an additional, rapid way to increase the transport of bicarbonate ions to the oceans (Knapp and Tipper, 2022).

From a Swiss perspective it is important that enhanced weathering ("ex-situ carbonation") of metamorphic and plutonic host rocks present in large quantities in Switzerland has the highest potential to permanently store CO_2 in Switzerland (Ladner *et al.*, 2023). However, it is also important to realize that such enhanced weathering requires mobilization of large quantities of host rock – per ton of CO_2 to be stored, about 2-5 tons of rock is needed. Removing 1 Mt CO_2 per year would require excavation of rock material in a similar order of magnitude as currently performed to produce feedstock material for the cement industry (ca. 5 Mt per year) (Ladner *et al.*, 2023).

Enhanced Weathering comes along with potential risks and co-benefits, which are – similar to the CDR effectiveness – often location- and case-specific, depending for example on climate conditions, land cover, and application rate (Lehmann and Possinger, 2020; Pogge von Strandmann *et al.*, 2022). Among the risks are potential releases of metals and persistent organic compounds (compounds resistant to environmental degradation). EW has mainly been considered for application in agriculture, less so in forestry, and occasionally in natural ecosystems and ecosystems under restoration (Beerling *et al.*, 2020). One of the key co-benefits of EW in agriculture is the fact that crop production can increase. The added rock contains essential plant nutrients, such as calcium and magnesium, as well as potassium and micronutrients that promote crop production in several ways (Lehmann and Possinger, 2020). EW also enhances soil fertility by buffering low soil pH and stabilizing soil organic matter, and can improve soil water retention, thereby promoting plant growth and CDR in agriculture (Beerling *et al.*, 2020).

One of the main shortcomings of EW as CDR method today is the lack of a verifiable and cost-effective carbon accounting approach (Amann and Hartmann, 2022). Quantifying the actual CO_2 removal also remains challenging because it depends on many other factors besides the type of rock used. The particle size of the applied rock can impact the dissolution rate. A smaller particle size increases the dissolution rate, while a larger particle size has the opposite effect, which affects the CO_2 removal rate. Other factors, such as the application rate, climatic conditions, and land cover, can increase or decrease the removal efficiency of CO_2 (Lefebvre *et al.*, 2019; Tan and Aviso, 2021; Eufrasio *et al.*, 2022; Abdalqadir *et al.*, 2023; Foteinis, Campbell and Renforth, 2023; Guo *et al.*, 2023).

2.2.5 Carbon Capture and Utilization with long-term storage of CO_2 (CCUS)

Carbon Capture and Utilization (CCU) refers to the capture of CO_2 from either the atmosphere (via DAC or growing biomass) or point sources such as fossil fuel combustion and its subsequent use for various purposes, e.g., hydrocarbon fuel production, production of chemicals or plastics, or as additive for construction materials (Figure 2.10). The direct use of biomass (wood) as construction material, globally most relevant in an urban context (Rodriguez Mendez *et al.*, 2024), can also be considered as (indirect) CCU. CCU only qualifies as CDR method, if the CO_2 is either of biogenic origin ("captured" by biomass) or directly captured from the atmosphere, AND if the use of CO_2 stores it – at least large fractions – over decades to centuries (Hepburn *et al.*, 2019; de Kleijne *et al.*, 2022).

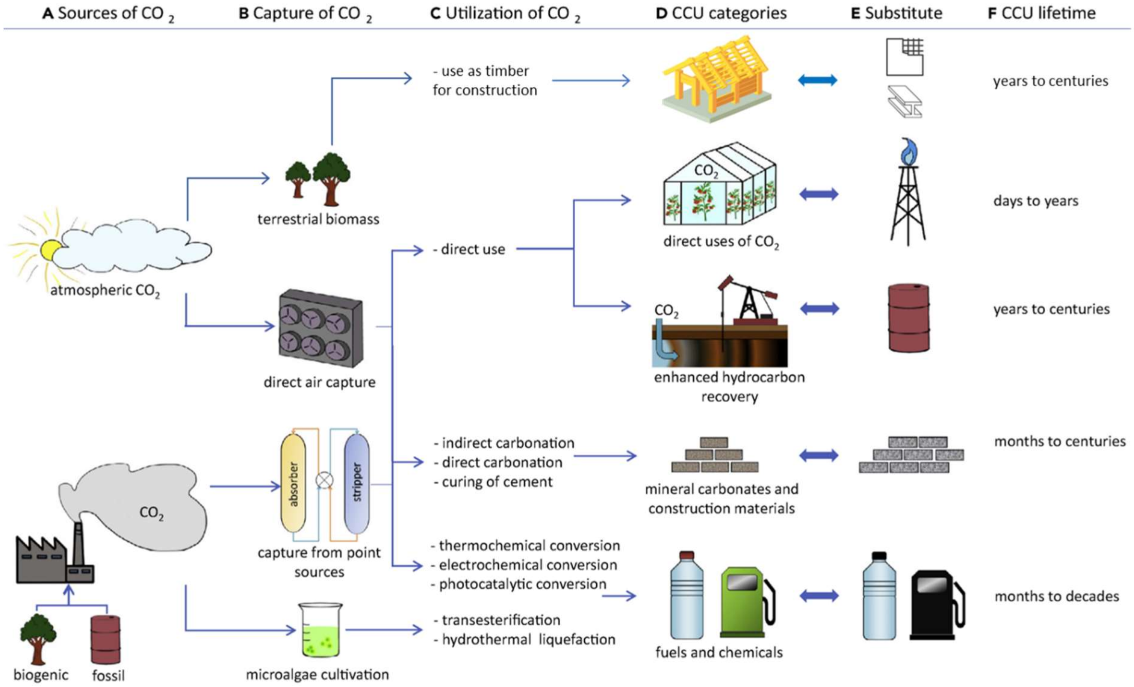

Figure 2.10: General scope of CCU, adapted from (de Kleijne et al., 2022).

The questions to which extent a short- to mid-term temporal removal (i.e., for less than 100 years) of CO_2 from the atmosphere provides climate benefits (i.e., reduces radiative forcing) and what most appropriate climate metrics would be requires further research. Recent work by (de Kleijne *et al.*, 2022) suggests to use the GWP factors shown in Table 2.3 for CO_2 stored in CCU-based products over a certain period of time. The GWP of zero for CO_2 emissions delayed by 100 years or more indicates "permanent CO_2 removal" here. However, as very recently demonstrated, CO_2 removal for a period of 100 years is not equivalent to permanent removal in terms of climate impacts (Brunner, Hausfather and Knutti, 2024). Moreover, a broadly agreed upon dynamic concept to account for temporal removal of biogenic CO_2 via its use in products and the resulting climate impacts is currently still missing (Brander and Broekhoff, 2023; Matthews *et al.*, 2023) and would also have to consider counterfactual scenarios in terms of forestry and wood use (in the context of using timber as construction material – see associated discussion in section 2.2.6). Such a dynamic concept could also be applied to biochar-to-soil applications, as a fraction of the carbon in biochar is released before 100 years after application.[25]

Table 2.3: Global Warming Potential (GWP) factors for "delayed CO_2 emissions" due to temporary storage of CO_2 in CCU products using a 100 year time horizon as calculated by (de Kleijne et al., 2022).

"Lifetime of CCU product" equivalent to delay in CO_2 emissions	0–0.5 years	0.5–1 year	1 year	5 years	10 years	25 years	50 years	>100 years
GWP (for those delayed CO_2 emissions)	1	0.99	0.98	0.92	0.85	0.67	0.42	0

Whether and which benefits temporary (or "impermanent") removal of CO_2 from the atmosphere provides depends also on the goal of an intervention and on the long-term perspective, e.g., whether

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[25] Due to uncertainties regarding the timing of these emissions and the lack of an agreed upon dynamic climate impact accounting concept, we consider carbon released within 100 years after biochar application as "not permanently removed" in our biochar-to-soil LCA, i.e., apply a GWP of 1 to these CO_2 emissions which occur within 100 years after biochar application.

reducing peak warming or cumulative warming is in focus. Recent work indicates that re-release of temporary stored carbon results in more warming than if no carbon had been stored, but also that this so-called “temperature asymmetry” is non-trivial and depends on the background emissions scenario (Reisinger, 2023). Short-term storage may help flatten and shorten the peak temperature rise by holding carbon out of the atmosphere while other measure are put in place (Marland, 2023). Very recent findings from (Brunner, Hausfather and Knutti, 2024) suggest that “a CO_2 storage period of less than 1000 years is insufficient for neutralizing remaining fossil CO_2 emissions under net zero emissions.”

2.2.6 Accounting for biogenic carbon flows in LCA in the context of wood (timber) as construction material

Wood has gained prominence as a sustainable construction material due to its renewable nature and carbon sequestration potential. However, leveraging wood to capture and temporarily store carbon involves complex considerations spanning forest management, material and building life cycles, and the evolving landscape of a decarbonizing economy. A comprehensive quantitative assessment of the climate impacts of using wood as construction material (including cascade use cases) is thus out of scope of this work. Instead, we discuss associated challenges in the following and provide a simple case study applying a newly developed dynamic, time-explicit accounting framework in section 3.6.

In general, looking at the use of wood from a climate perspective, all that matters is the total amount of CO_2 in the atmosphere, regardless of its origin, be it biogenic- or fossil carbon (Strengers *et al.*, 2024). Put differently, minimizing the negative impact on climate change means maximizing the total biogenic carbon stock in forests and the technosphere, as well as the fossil carbon stock in reserves, while minimizing the release of CO_2 into the atmosphere. In the following, the different aspects dealing with biogenic carbon accounting are briefly discussed.

Biogenic Carbon vs CO_2

Biogenic carbon refers to carbon that is part of the natural carbon cycle, such as carbon stored in plants and trees. Unlike fossil carbon, which is part of long-term geological carbon cycles, biogenic carbon is considered “renewable” because it is part of a relatively short-term cycle. However, it is a misconception to equate renewable to sustainable in this context because once carbon, be it biogenic or not, is turned into CO_2 through oxidation, methane through natural decomposition or ruminant digestive activity, or other greenhouse gasses, its origin is of no concern. For the climate, only the concentrations of greenhouse gases in the atmosphere are of importance, not the origins (Ahamer, 2022). Therefore, to assess the sustainability of using wood as a construction material (or other uses of wood), one needs to consider not only the life cycle impacts of both wood-based products as well as the alternative material they might replace, but also the opportunity costs of different forest management strategies, and the (potential) eventual release of the carbon stored in these wood-based materials (Peng *et al.*, 2023).

Accounting biogenic carbon in LCA in general and dynamic LCA in particular

The impact of wood-based materials is often evaluated through life cycle assessment (LCA), but because of the so-called “renewable” nature of wood-based products, there have been different approaches to model the release of or uptake of biogenic carbon throughout its life cycle. An overview of the various methods can be found by (Hoxha *et al.*, 2020), who classify three main approaches:

1. The ‘0/0 approach’, based on a carbon neutrality assumption in which the biogenic carbon released between harvest and end-of-life is balanced by the uptake of CO_2 during biomass growth. Only the release of methane is accounted for in terms of climate impacts.
2. The ‘-1/+1’ approach, which tracks all the biogenic carbon flows and uptake of CO_2 (-1) into- and release from biogenic carbon sources (+1) are modelled.
3. So-called “dynamic LCA” (Levasseur *et al.*, 2010), which considers the timing of the uptake and release of carbon from and to the atmosphere and associated climate impacts. This

approach introduces time-dependent characterization factors, which consider the residence time of GHGs in the atmosphere. This provides a more accurate representation of the carbon dynamics and thus climate impacts associated with wood as a construction material and wood harvesting in general (Peng *et al.*, 2023).

The first two approaches are not useful in the context of meaningfully quantifying climate benefits of long-term storage of biogenic CO_2 in products such as (wooden) construction materials and cascade utilization of wooden construction materials. Dynamic LCA is currently the only framework that allows for a comprehensive assessment of all aspects of forestry products, including the timing of carbon sequestration and emissions. Figure 2.11 shows a schematic overview of a system definition that can be used for such an assessment. The green blocks indicate the forest modelling, and the yellow blocks show the submodules that are subject to technological change and require a prospective analysis (See the section on "material displacement factors and prospective analysis" below).

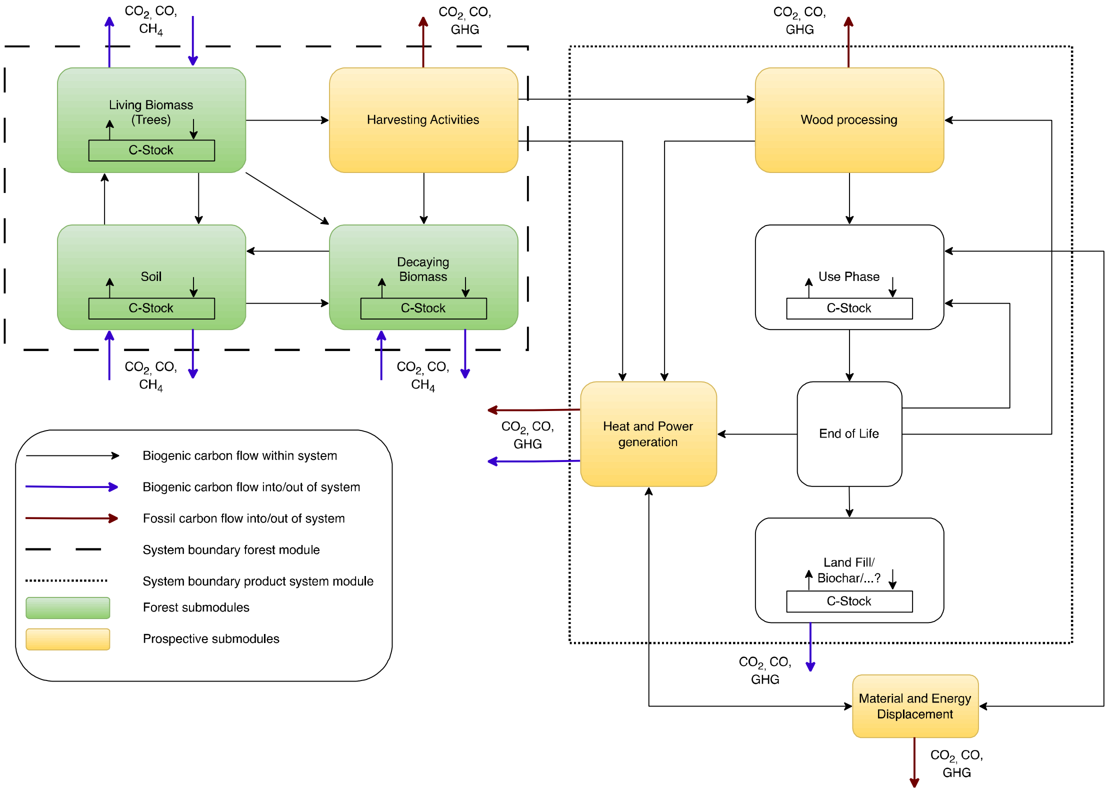

Figure 2.11: A comprehensive system definition for the assessment of wood products in the context of CO_2 removal from the atmosphere. The forest system is distinguished from the technosphere. The yellow process modules are subject to technological change and need a prospective assessment, especially in the context of end-of-life activities/processes.

Forest management scenarios under changing forests

An important factor to consider when it comes to the use of harvested wood products is the opportunity costs of different scenarios (Lefebvre *et al.*, 2021; Erb *et al.*, 2022). Both in terms of forest management (Seppälä *et al.*, 2019; Strengers *et al.*, 2024) and the replaced materials (decarbonizing economy). While European forests have seen an increase in carbon stock over the last few decades, acting effectively as a carbon sink (Kilpelainen and Peltola, 2022), the future development of sequestration and storage is highly dependent on both forest management (Nabuurs *et al.*, 2017; Kilpelainen and Peltola, 2022) and climate change effects (Kilpelainen and Peltola, 2022). The latter includes disturbances such as droughts as seen in recent years. This may lead to a change in forest management practices and different tree species, which in turn will have a strong influence on the sequestration and storage capacity as well as the availability of harvested wood products and, with that, the material displacement potential of wood. To complicate matters further, it is most often misleading to attribute growing or declining carbon stocks in managed forests to specific management practices. Instead, these changes in carbon stocks are principally a reflection of a non-uniform age distribution of the stands of trees in the forest (Strengers *et al.*, 2024).

Storage and cascading use cases

As discussed above, the framework of dynamic LCA accounts for the timing of emissions and, therefore, captures the effect of temporary carbon storage acting as a CO_2 sink in short or long-lived wood products. Furthermore, potential reuse and cascading options for the use of wood products at their "end-of-life" as, for example, a construction material or biogenic feedstock for energy production need to be assessed. As such, a dynamic LCA framework for accounting of biogenic CO_2 stocks and flows will therefore represent the benefits of temporarily storing CO_2 in for example wooden building materials, independently any counterfactual scenario of wood use.

Material displacement factors and prospective analysis

When using wood as construction material, a different, potentially more carbon-intensive material, such as steel or concrete, can be replaced. The so-called material displacement factor (DF) expresses the efficiency of using wood-based products or fuels instead of fossil-based ones to reduce net GHG emissions. They are given as the amount of fossil carbon saved per ton of wood carbon used. Estimates for the DFs of different products span an extensive range, leading (Seppälä *et al.*, 2019) to develop the concept of "required" displacement factors (RDFs), which provide the values for the DFs needed for two different forest management scenarios to have a similar climate performance. While the RDFs only depend on the forest management scenarios and thus on climate change, the actual material displacement depends, of course, on the life cycle impacts of the displaced material or fuel. However, as the economy changes and for example the energy sector, steel and concrete production processes shift towards renewable sources and potentially towards net-zero GHG emissions, the material carbon displacement effect of using wood may diminish. This emphasizes the need for a holistic approach to decarbonization, considering not only the construction materials but also the overall energy and resource consumption throughout the building's life cycle. Such aspects can be assessed with prospective LCA, in which future scenarios of development are considered (Sacchi *et al.*, 2022).

Regionalisation

The performance of wood-based products heavily depends on specific tree species present, local forest management and regional supply chain conditions, which might all change in the future, also due to climate change (Wessely *et al.*, 2024). The importance of local and regional aspects also holds true for previously discussed material displacement factors and the prospective LCA.

3 Life Cycle Assessment (LCA)

Environmental Life Cycle Assessment (LCA) is the method of choice to quantify environmental burdens associated with the production, use and end-of-life of products (ISO, 2006a, 2006b; Hauschild, Rosenbaum and Irving Olsen, 2018).[26] Specific recommendations for LCA of CDR have been provided by a few scholars (Terlouw, Bauer, *et al.*, 2021; Brander, 2024; Butnar *et al.*, 2024; Nordahl *et al.*, 2024). Within this project, LCA is limited to small-scale, attributional assessments of current or near-future[27] product systems (Earles and Halog, 2011; Zamagni *et al.*, 2012; Schaubroeck *et al.*, 2021), in which "single units" are evaluated regarding their environmental performance. A consequential analysis, in which CDR is scaled up to the required quantities over the next decades and effects of large-scale application on the level of the entire energy system or economy would be investigated, is out of scope of this work, but should be performed in the future (see section 5), as attributional LCA fails to quantify the total system-wide change in emissions and removals caused by an intervention or action and is therefore – according to some scholars – not appropriate for quantifying net removals for offset credits (Brander, 2024). This fact should be considered when interpreting the results – these do not represent any effects of large-scale implementation on a system level, for example the strong interdependencies of some CDR methods such as DACCS and BECCS and the energy system as a whole. Also, this report and the LCAs for biochar and BECCS do not allow to answer the question which use of the limited amounts of sustainable biomass in Switzerland would be most beneficial in terms of climate or biodiversity impacts in a conclusive way. Nevertheless, the LCA results provided here and in section 4 as well as by the LCA tool developed are useful, as they provide a first good quantitative indication regarding possible net carbon removal efficiencies of several CDR methods in a Swiss context,, allow for conclusions regarding the conditions which must be met for the CDR methods addressed to provide effective net GHG removals from the atmosphere in general and can be used to identify key parameters in this respect. Further, LCI established are very well suited for follow-up activities as outlined in section 5.

The following sub-sections provide an overview of selected, literature based LCA results for some CDR options, representing impacts on climate change (or life cycle GHG emissions) using global warming potentials for a time horizon of 100 years ("GWP100"). In general, the LCA performed within this project builds upon the recommendations provided by (Terlouw, Bauer, *et al.*, 2021), who stressed the importance of consistency and transparency in comparative LCA of CDR methods. Not all the product systems addressed in this section are incorporated in the LCA tool, which is explained in section 4, and which is also used to generate new LCA results to quantify net CO_2 removal rates.

3.1 Direct Air Carbon Capture and Storage (DACCS)

Several LCAs have been performed so far, for both high- and low-temperature capture technologies (de Jonge *et al.*, 2019; Liu *et al.*, 2020; Deutz and Bardow, 2021; Madhu *et al.*, 2021; Terlouw, Treyer, *et al.*, 2021; Qiu *et al.*, 2022; Casaban and Tsalaporta, 2023). All these studies agree on the fact that low-carbon energy supply for DAC operation is key to minimize indirect GHG emissions and achieve high carbon removal efficiencies. Here, we provide LCA results of our own analysis (Terlouw, Treyer, *et al.*, 2021) to highlight key factors determining the outcomes of the LCA: an LCA of a low-temperature, adsorption-based (solid sorbent) DAC process representing Climeworks technology.

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[26] There are claims that LCA – especially in the context of CDR – is ill-suited for quantitative analysis due to ambiguities and insatiable data requirements (Lackner *et al.*, 2023). However, we consider such claims as non-substantiated and the alternative proposed by (Lackner *et al.*, 2023) as very far-fetched.

[27] The term "near-future" refers to the fact that some of the product systems for which LCA is performed are not yet commercialized and it will likely take some years until they can remove CO_2 from the atmosphere in practice. Our LCA represents those product systems as if they would be commercially available today, based on currently available information. Ideally, such "near-future" product systems would be evaluated applying prospective LCA, in which the background inventories are modified and represent some future point in time (Sacchi *et al.*, 2022). This is, however, out of scope of this work.

Moreover, our LCA tool (see section 4) also contains a high-temperature DAC configuration modelled according to (Qiu *et al.*, 2022).

System boundaries of the low-temperature DAC product system are visualized in Figure 3.1. Key process is the operation of the DAC unit, which needs heat and electricity as well as a sorbent. We included several DAC configurations and energy supply options including autonomous systems directly supplied by renewable energy and able to operate at remote locations disconnected from the power grid. Heat can be provided by an industrial heat pump, which can be operated using electricity from different sources, by any waste heat source, or by a solar collector in combination with a heat storage unit. Electricity can be provided by the grid or by dedicated wind and solar power installations in combination with a battery electricity storage. The captured CO_2 is compressed and transported via pipeline to be injected into a geological reservoir for permanent storage. All these processes consume electricity and CO_2 transport by pipeline is associated with (minor) CO_2 emissions due to leakage.

This analysis does not take into account the impact of ambient temperature and humidity on the performance of the CO_2 capture process (An, Farooqui and McCoy, 2022); however, we consider this aspect in the final version of our LCA tool (see section 4).

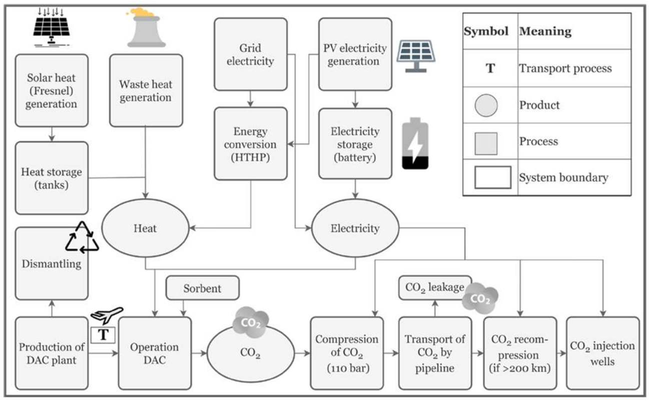

Figure 3.1: System boundaries in the LCA of DACCS according to (Terlouw, Treyer, *et al.*, 2021).

The net-effectiveness (or efficiency) of CO_2 removal via DACCS from a life-cycle perspective is mainly determined by the GHG emissions associated with energy supply for the DAC unit (Figure 3.2).

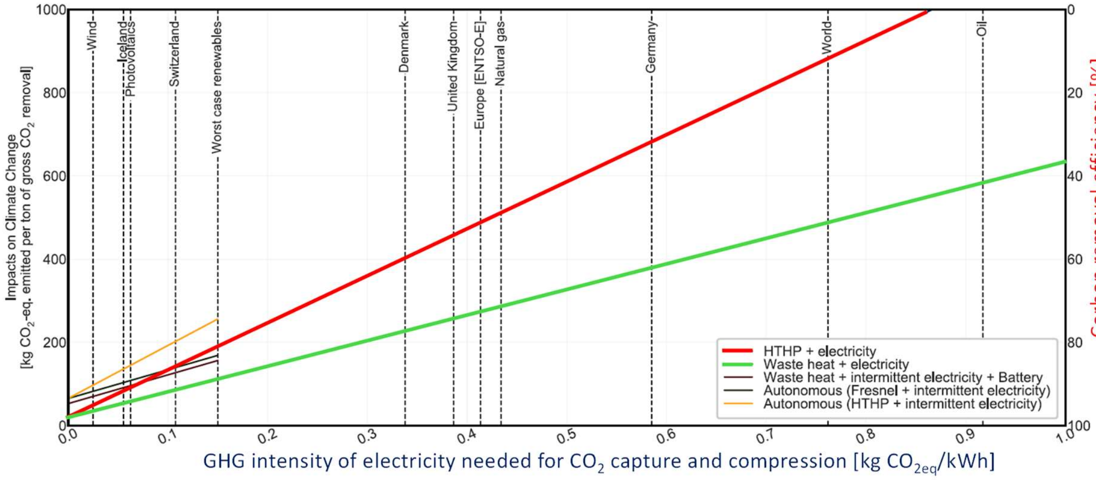

Figure 3.2: Life-cycle GHG emissions of a DACCS system as a function of the GHG emission intensity of the energy needed for operation of the DAC unit (Terlouw, Treyer, *et al.*, 2021). HTHP: High-temperature heat pump; "Fresnel": Solar heat collector. Vertical dashed lines represent the average life cycle GHG emission intensities of technology- or country-specific electricity supply. Carbon removal efficiency refers to the net-effectiveness of permanent CO_2 removal considering all GHG emissions caused by the DACCS product system.

If both electricity and heat are low in terms of GHG emissions (which includes electricity from hydro, solar, wind and geothermal power, solar and geothermal heat), this net-effectiveness of CO_2 removal can be above 90%. Autonomous systems directly supplied with renewable energy from dedicated units include energy storage to allow autonomous operation and exhibit higher GHG emissions in the construction phase. However, this decreases their net-effectiveness only marginally. Also, GHG emissions from CO_2 transport and storage only represent a very small contribution for the default transport distance for CO_2 of 200 kilometres (Terlouw, Treyer, *et al.*, 2021). For CO_2 transport via pipeline this holds also true for distances up to a few thousand kilometres (see section 4).

3.2 Biochar-to-soil applications

There is a relatively large body of literature regarding LCA of biochar-to-soil applications (Matuštík, Hnátková and Kočí, 2020; Azzi, Karltun and Sundberg, 2021, 2022; Matuštík, Pohořelý and Kočí, 2022; Tisserant *et al.*, 2022; Lenk *et al.*, 2024; Xia *et al.*, 2024). However, their quality in terms of e.g., modelling of system boundaries, assumptions regarding permanence of CO_2 removal, and consideration of substitution effects, is often questionable and therefore results are not always reliable (Terlouw, Bauer, *et al.*, 2021). Furthermore, available studies are often case-specific and thus either not of general value and/or not representative for Swiss conditions (for example, in terms of substituted energy carriers, soil properties, or biomass feedstock). We therefore conduct a parameterized LCA of biochar-to-soil applications, which aims at covering a broad range of potential boundary conditions (including those likely to include Switzerland) and provides LCA results specific for those (Hoeskuldsdottir, 2022). Figure 3.3 shows the system boundaries with processes included and potential effects excluded. To a large extent, this parameterized LCA is also included in our LCA tool (section 4).

The process chain starts with feedstock production, processing, and transport to the pyrolysis plant. In case of residual or waste biomass feedstock, environmental burdens of the feedstock production are outside the system boundaries and the residual material enters the system free of environmental burdens (apart from those associated with waste collection and transport to the pyrolysis plant).[28] The pyrolysis process turns feedstock into biochar, syngas, and bio-oil. Syngas and bio-oil are assumed to be used for heat and electricity generation in a combined heat and power (CHP) unit. Part of the generated heat is used for feedstock drying and operating the pyrolysis plant. Our analysis is limited to dry biomass types, as pyrolysis of wet biomass such as manure makes less sense from an energy perspective, as external heat would be required. Biochar is transported to the point of application as soil amendment, where it represents a long-term carbon storage and thus CDR.

Heat and electricity produced by the CHP from syngas and bio-oil, which are not internally used, are accounted for via system expansion by “emission credits”, corresponding to emissions of specific sources of heat and electricity, which are assumed to be substituted by the excess heat and electricity produced by the biochar product system. Important is the distinction between CO_2 removal due to biochar-to-soil application and reduction of CO_2 emissions elsewhere due to substitution of heat and electricity generation, often referred to as “avoided emissions”. The latter depends on a baseline scenario, which determines the replaced type of heat and electricity and the corresponding emission reduction. The replaced type of heat and electricity also depends on the time horizon considered: from a short-term perspective, the operation of existing capacities will be affected, while from a long-term perspective, installation of new and retirement of existing capacities will be affected. Consideration of a reduction in fertilizer consumption is modelled as an optional element, as whether biochar application can lead to a reduction in fertilizer consumption depends on soil characteristics (Cobo *et al.*, 2023) and plant type and must be addressed in a case-specific way.

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[28] This modeling choice corresponds to the system model “allocation, cut-off by classification” of the ecoinvent database and the UVEK LCA database.

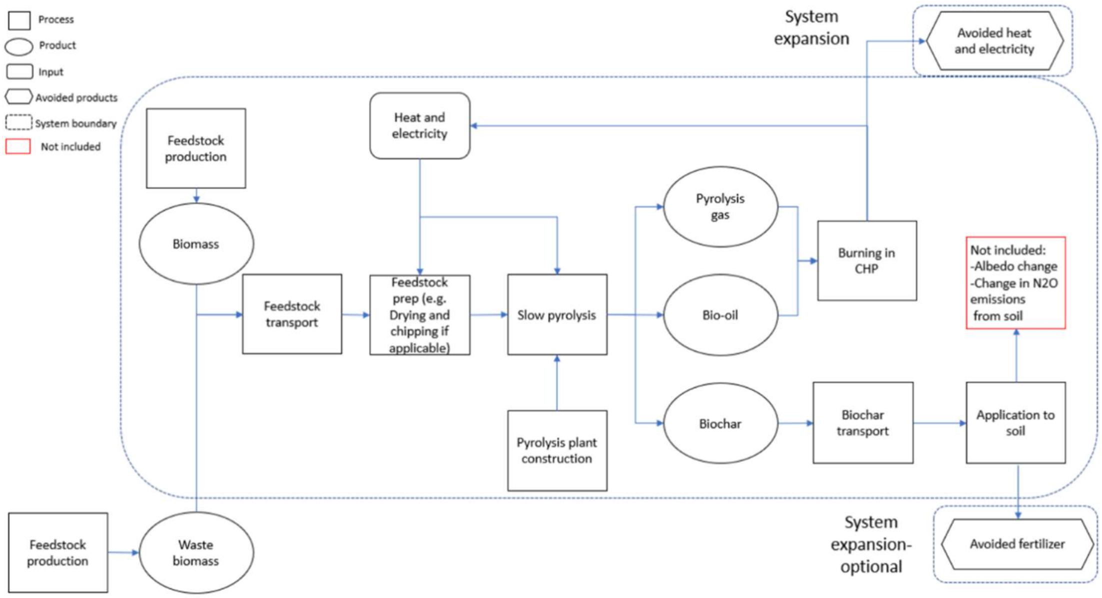

Figure 3.3: System boundaries of the biochar-to-soil LCA (Hoeskuldsdottir, 2022). The scheme does not include all potential side-effects such as impacts on soil biology, organic soil carbon, or contaminants.

Our LCA considers a number of interdependencies between parameters based on empirical evidence from literature (Woolf *et al.*, 2021; Tisserant *et al.*, 2022) and as qualitatively shown in Table 3.1. For example, an increase in pyrolysis temperature reduces biochar and tar yield, while it increases the carbon fraction in biochar, syngas yield and its heating value as well as the biochar stability factor in soil. All of these interdependencies are quantitatively covered in the LCA (see (Hoeskuldsdottir, 2022) for all details), as they have an effect on LCA results.

Table 3.1: Qualitative representation of interdependencies within the LCA of biochar-to-soil applications as modelled in (Hoeskuldsdottir, 2022).

Increase in…	…leads to	of
Pyrolysis temperature	Reduction ↓	Biochar yield
	Increase ↑	Carbon fraction in biochar
	Increase ↑	Syngas yield
	Increase ↑	Heating value of syngas
	Reduction ↓	Tar yield
	Increase ↑	Biochar stability factor
Soil temperature	Reduction ↓	Carbon stability factor
Feedstock lignin content	Increase ↑	Biochar yield
Feedstock moisture	Increase ↑	Energy demand for drying
	Reduction ↓	Credits for avoided heat and electricity generation
Feedstock ash content	Reduction ↓	Biochar yield
	Reduction ↓	Organic carbon fraction in biochar
Carbon stability factor	Increase ↑	Carbon dioxide removal
Biochar carbon fraction	Increase ↑	Carbon dioxide removal

Not included in our LCA model are changes in albedo due to biochar-to-soil application, which would affect surface temperatures, climate impacts of indirect land use change because of the use of dedicated biomass crops, and potential changes in methane and nitrogen oxide emissions from soils. This effect on N_2O emissions is a topic of ongoing research and based on the currently available evidence (Borchard *et al.*, 2019; Guenet *et al.*, 2021; Shakoor *et al.*, 2021; Lyu *et al.*, 2022), we were not able to determine specific values for N_2O emission reductions, which could be applied in a generic way.

Figure 3.4 shows life cycle impacts on climate change for biochar-to-soil application (per ton of biochar applied to soil) for three different cases in terms of substituted heat and electricity (i.e., excess energy from the conversion of syngas and bio-oil not used for feedstock drying and pyrolysis operation is assumed to replace other types of heat and power generation). Parameters are specified equally otherwise: willow with a moisture content of 40% is used as feedstock; pyrolysis temperature is 500°C, soil temperature assumed to be 14.9°C (global mean annual cropland-temperature (Woolf *et al.*, 2021)), credits for potential reduction in fertilizer consumption are not included, and overall transport distance (for biomass and biochar) is assumed to be 205 kilometres.

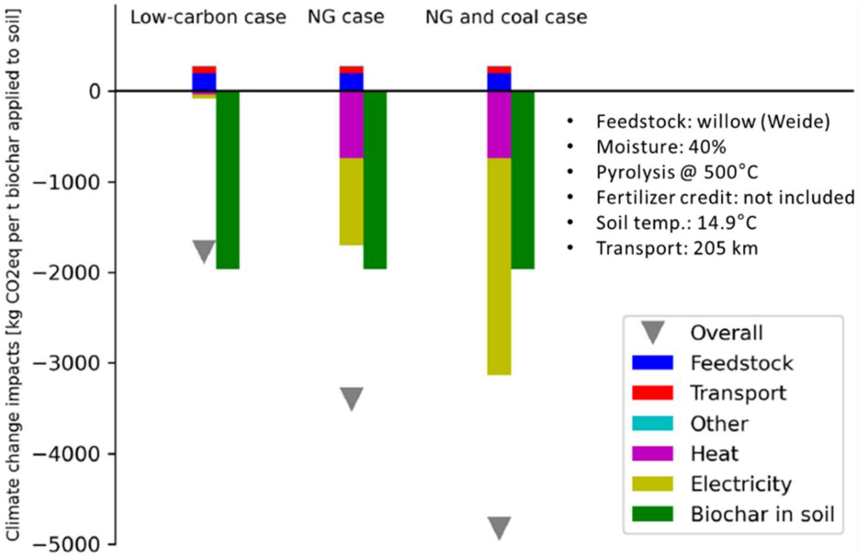

Figure 3.4: Impacts on climate change per ton of biochar applied to soil (Hoeskuldsdottir, 2022). NG: Natural gas. Specific cases here are primarily selected and shown to highlight the importance of substitution effects. "Biochar in soil" represents the amount of CO_2 permanently removed from the atmosphere, while the negative emissions from "heat" and "electricity" represent avoided emissions due to substitution of replaced energy supply.

The "low-carbon case" corresponds to substitution of electricity from wind turbines and wood heating; the natural gas (NG) case corresponds to substitution of electricity from a natural gas power plant and heat from a gas boiler; the "NG and coal case" corresponds to substitution of heat from a NG boiler and electricity from a coal power plant. While the amount of "permanently" (i.e., for at least 100 years[29]) removed CO_2 (in Figure 3.4: "biochar in soil") is equal in all cases, the emission reduction due to substitution of energy supply is case-specific and shows large differences. In general, the GHG emissions due to feedstock supply, transport and other activities are small compared to the amount of CO_2 removed from the atmosphere and the GHG emission credits in case of fossil energy is substituted. From a long-term perspective, however, it seems likely that emission credits due to avoided GHG emissions from fossil energy supply will become less relevant, if the energy system transitions towards net-zero GHG emissions.

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[29] Most recent findings from (Brunner, Hausfather and Knutti, 2024) show that using a CO_2 removal period of 100 years as equivalent to permanent CO_2 removal is insufficient. (Brunner, Hausfather and Knutti, 2024) conclude that "that a CO_2 storage period of less than 1000 years is insufficient for neutralizing remaining fossil CO_2 emissions under net zero emissions». We have, however, not been able to include this finding in our quantitative assessment, as it has been published during the final revision of this report.

3.3 Bioenergy with Carbon Capture and Storage (BECCS)

We have performed LCA of wood combustion with CCS building upon (Volkart, Bauer and Boulet, 2013), as included in the LCA tool (see section 4), hydrogen production via wood gasification with CCS and biomethane reforming with CCS (Antonini *et al.*, 2020, 2021). The latter two BECCS options – using wood from sustainable forestry in existing forests and residual biomass from agriculture, respectively – show negative GHG emissions from a life-cycle perspective, i.e., permanently remove CO_2 from the atmosphere. Other BECCS options – partially not addressed here – include anaerobic digestion of wet biomass with CCS or use of the captured biogenic CO_2 for long-term storage in construction materials such as recycled concrete aggregates (see section 3.4).

It is important to note that our LCA of wood combustion with CCS is based on the assumption of “carbon neutrality” of the product system without the CCS components, meaning that producing biomass from forests for bioenergy results in zero or negligible net emissions of CO_2 to the atmosphere, when the complete life cycle of forest growth (and re-growth), harvesting and consumption of biomass is considered. This can occur if CO_2 emissions from harvesting and using forest biomass, including combustion for bioenergy, are exactly balanced by carbon sequestration in the forests that produced the biomass (Figure 3.5). This simplifying assumption is, however, not always justified – forest carbon stocks can be positively and negatively affected by management practices involving bioenergy production (or also biomass use for products) (Strengers *et al.*, 2024).

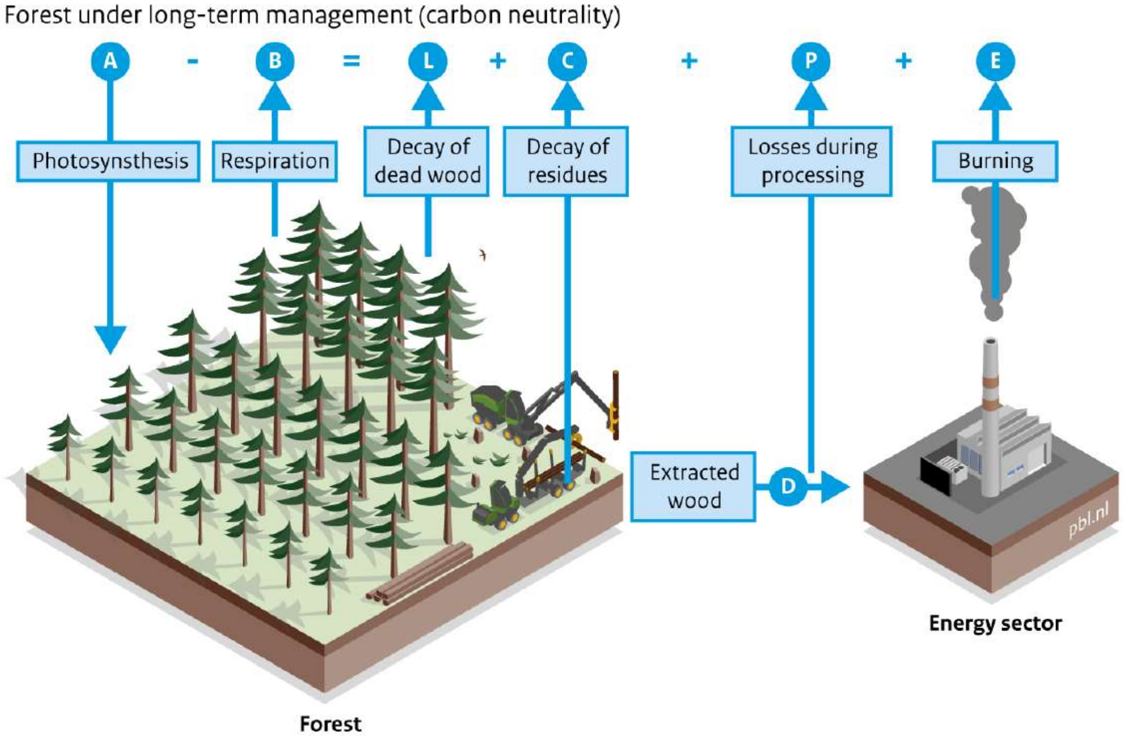

Figure 3.5: Carbon balance of a “carbon neutral” bioenergy system considering all carbon flows along the chain from photosynthesis to biomass combustion (Strengers et al., 2024). Carbon neutrality occurs when the net uptake of CO_2 during forest growth (A minus B) perfectly balances out the losses to the atmosphere (L, C, P, E).

(Strengers *et al.*, 2024) list four basic conditions for carbon neutrality of biomass:

- “The quantities of biomass being extracted from forests are stable over time assuming harvesting is not constrained by factors such as uneven distribution of tree/stand ages.
- The quantities of biomass being extracted do not exceed the regrowth of biomass.
- The forest management practices involved in biomass supply are constant over time (such as, levels of thinning and rotation ages in stands being kept the same).

- The existing uses of biomass are maintained (such as, biomass is not diverted from other existing uses such as the manufacture of material products to use for bioenergy)."

Further, they add that "…in real situations, perfect carbon neutrality is likely to occur only in exceptional circumstances, because the rates of biomass supply and the forest management approaches to produce the biomass are rarely unchanging over time." (Strengers *et al.*, 2024).

Biomass (both wood and biomethane) can also be used to produce hydrogen, including capturing and sequestering CO_2 emitted during the hydrogen production process. Figure 3.6 schematically shows system boundaries of the LCA for such a hydrogen production system from biomass. Importantly, the upstream activities of the biomethane production chain up to (and including) biogas production via anaerobic digestion of residual wet biomass and thus their environmental burdens are assigned to the agricultural sector, which generates the biogenic waste. Its anaerobic digestion is considered as a waste treatment service and therefore, the biogas enters the product system without environmental burdens.[30] However, the carbon balance has been calculated irrespectively of this modelling choice to represent physical flows correctly – thus, carbon removal is assigned to the BECCS processes, i.e., the hydrogen production.

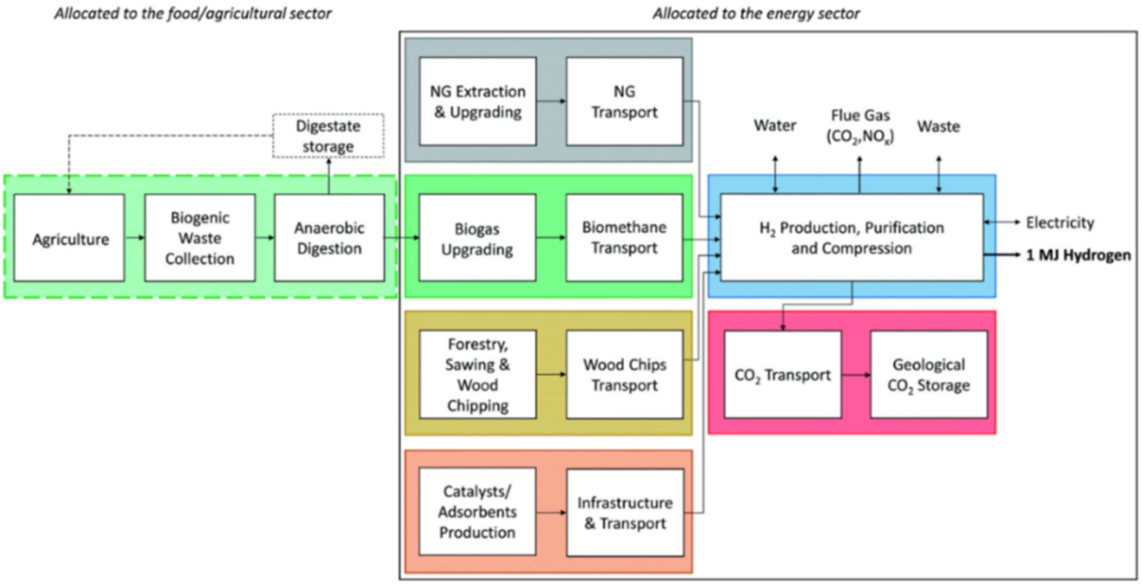

Figure 3.6: System boundaries in the LCA of hydrogen production via wood gasification and biomethane reforming with (and without) CCS (Antonini *et al.*, 2020, 2021).

Figure 3.7 shows life cycle GHG emissions of hydrogen production from wood and biomethane (and natural gas as reference for comparison) with and without CCS (per kg of hydrogen produced). All biomass-based production pathways with CCS remove CO_2 from the atmosphere from a life-cycle perspective (corresponding to negative GHG emissions). Overall, these results are mainly driven by CO_2 capture rates at the hydrogen production facilities. Other processes – except of natural gas supply chain related GHG emissions delivering the feedstock for the conventional reference system, which can be substantial (Bauer *et al.*, 2022) – play minor roles. Importantly, potentials of both wood from sustainable forestry and agricultural residues are limited. Using purpose-grown biomass would exhibit higher impacts on climate change due to e.g., use of fertilizers and induced land use changes.

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[30] This modeling choice corresponds to the system model "allocation, cut-off by classification" of the ecoinvent database and the UVEK LCA database.

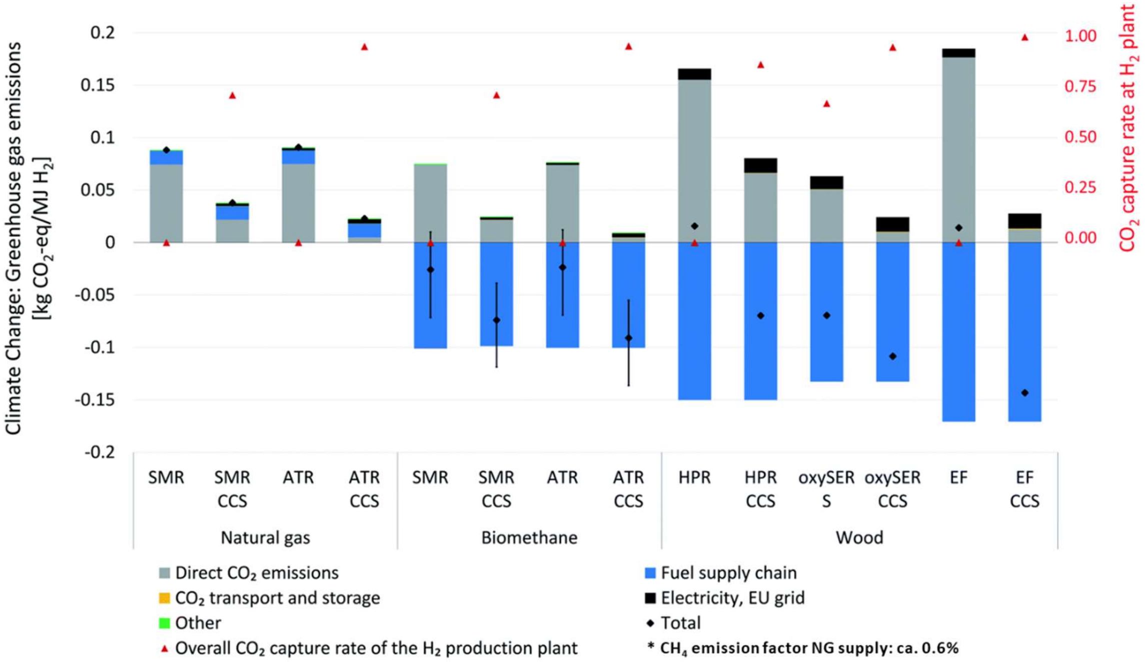

Figure 3.7: Impacts on climate change in terms of life-cycle GHG emissions due to hydrogen production from natural gas, biomethane and wood with and without CCS (Antonini et al., 2021). Error bars for the biomethane pathway indicate variability due to different disposal options for the digestate from the biogas production. SMR: Steam Methane Reforming; ATR: Autothermal Reforming; HPR: Heat Pipe Reformer; oxySER: Sorption enhanced reforming gasifier, EF: Entrained flow gasifier; EU grid: current average European electricity.

3.4 Mineralization of biogenic CO_2 in recycled concrete aggregates

Using biogenic CO_2 from a wastewater treatment plant and its mineralization in recycled concrete aggregates (RCA) represents a way of CO_2 capture and utilization for storage in long-lived products (Tiefenthaler *et al.*, 2021). The LCA shows that this value chain indeed removes CO_2 permanently from the atmosphere.

Figure 3.8 visualizes system boundaries of our LCA. Biogenic CO_2 can be supplied by any type of residual biomass treatment, in our case upgrading of biogas (i.e., basically separating CO_2 from CH_4) produced via anaerobic digestion of biogenic waste. Like in the BECCS product system which generates hydrogen from biomethane, the biogenic waste treatment and the biogas upgrading are considered to be waste treatment processes within the agricultural system and therefore, associated burdens are assigned to that part of the economy – the biogenic CO_2, as provided by the biogas upgrading enters the “concrete product system” without environmental burdens. This CO_2 is liquefied, transported by lorry to the mineralization plant, and evaporated there. It reacts with the recycled concrete aggregate from concrete recycling, originating from e.g., demolished buildings. Such mineralized (via CO_2 storage) recycled concrete aggregates store the biogenic CO_2 permanently and thus remove it from the atmosphere. Using these to produce new concrete elements could also lead to structural improvements of the concrete, decreasing the cement requirements. This would come along with reduced emissions of concrete production but requires further research and experiments. Such research and associated LCA has recently been performed as part of the “DemoUpCARMA” project with LCA results of CO_2 mineralization published in (Tiefenthaler *et al.*, 2024).[31]

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[31] http://www.demoupcarma.ethz.ch/en/home/

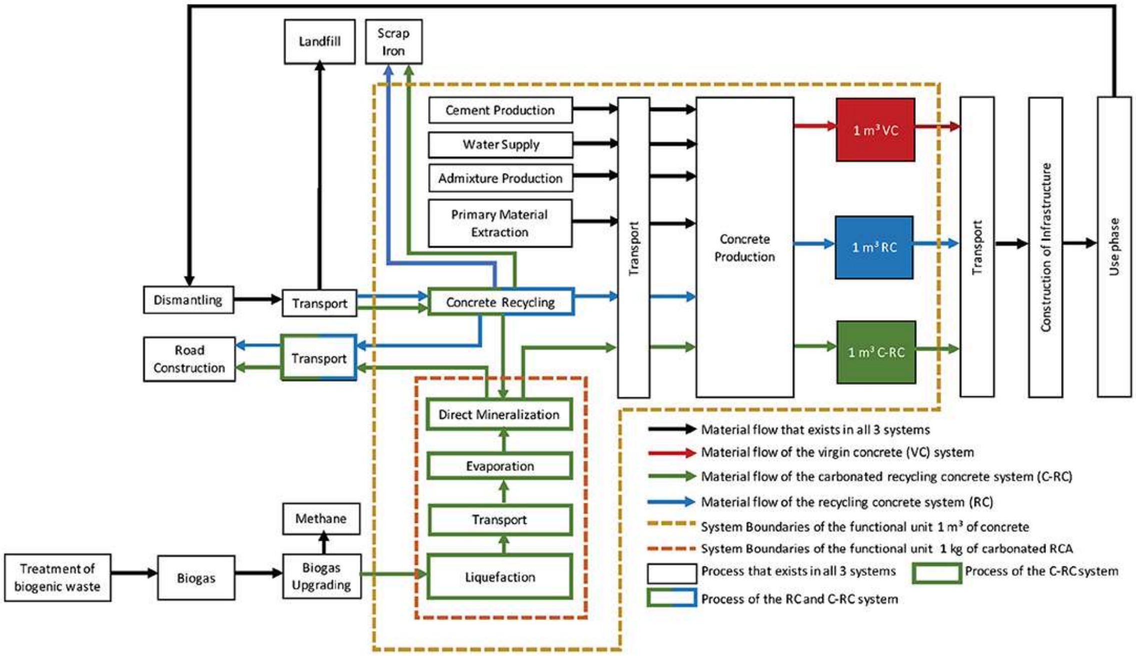

Figure 3.8: System boundaries of the product system considered in our LCA (Tiefenthaler *et al.*, 2021), comparing production of virgin concrete (VC) without recycled fractions, recycled concrete (RC), and carbonated recycled concrete (C-RC). RCA: Recycled Concrete Aggregate.

Figure 3.9 shows life cycle impacts on climate change (GWP100) in terms of GHG emissions associated with the value chain in focus of our LCA, i.e., storing biogenic CO_2 in recycled concrete aggregates. The left y-axes indicate the emissions of greenhouse gases per kilogram of recycled cement aggregates (RCA), the right ones the amount of GHG emissions per ton of CO_2 stored. Overall, the net effectiveness of CO_2 removal with this CDR method implemented in Switzerland, is around 93%, i.e., storing one ton of biogenic CO_2 and thus removing it from the atmosphere generates around 70 kg of GHG emissions. Main GHG emission contributions originate from the electricity supply of the CO_2 liquefaction process and the infrastructure needed along the value chain, mainly for the transport and the mineralization processes.

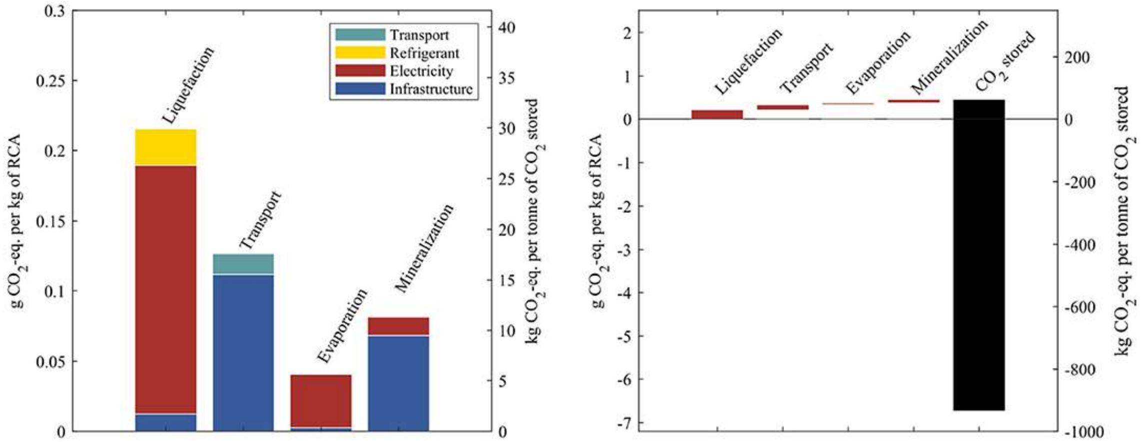

Figure 3.9: Life-cycle GHG emissions of the sub-processes of the negative emission value chain visualized along four main process categories (left) and cumulative GHG emission of the value chain, including the CO_2 removal (equal to negative emissions) of the mineralization plant (Tiefenthaler *et al.*, 2021).

3.5 Enhanced Weathering

Several LCA studies for Enhanced Weathering (EW) exist (Lefebvre *et al.*, 2019; Tan and Aviso, 2021; Chiquier *et al.*, 2022; Eufrasio *et al.*, 2022; Abdalqadir *et al.*, 2023; Feng and Hicks, 2023; Foteinis, Campbell and Renforth, 2023; Zhang *et al.*, 2023). Most of them use basalt or olivine rocks, but also demolition waste is considered. Figure 3.10 shows typical LCA product system boundaries for an enhanced weathering system (Lefebvre *et al.*, 2019). Key foreground processes are silicate material (or other mineral, e.g., olivine or basalt) extraction (including drilling, blasting, and loading of rocks), transport to crushing and crushing to the desired particle size, various loading activities, transport to the field and spreading of crushed material on the field.

Common findings of available studies are that 1) transport activities are among the key factors in the LCA with a major impact on the net CO_2 removal efficiency, that 2) energy demand and energy sources for crushing rock materials are less important, and that 3) the type of rock, as its properties determine the energy needed for crushing as well as the specific carbon removal capacity[32] (Ladner *et al.*, 2023), plays an important role. In general, there is a trade-off between particle size and carbon removal: smaller particles dissolve and take up CO_2 more quickly, but also need more energy for comminution (Foteinis, Campbell and Renforth, 2023). As both rock grinding and transportation represent the key parameters determining overall energy consumption, measures to reduce energy demand should be implemented, as large saving potentials seem to exist (De Marco *et al.*, 2024). Compared to natural rocks, the use of suited waste materials can considerable reduce GHG emissions (Abdalqadir *et al.*, 2023).

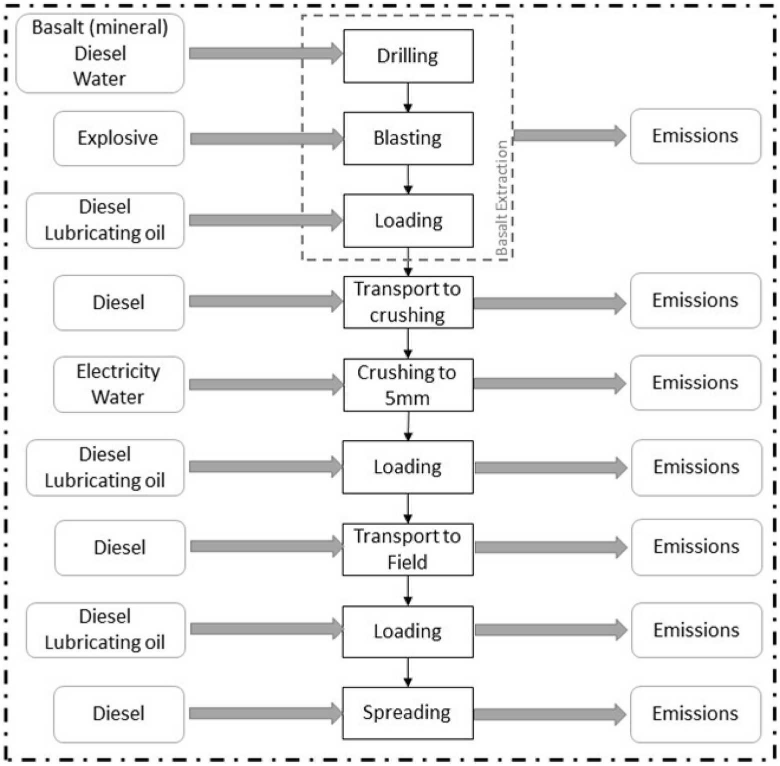

Figure 3.10: System boundaries of a typical enhanced weathering system including extraction, comminution, transport and spreading of basalt (Lefebvre *et al.*, 2019).

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[32] i.e., the amount of CO_2 stored by a ton of rock material.

3.6 Woody biomass utilization

In section 2.2.6, we discuss key considerations in biogenic carbon accounting. Here, we expand on this topic by comparing an LCA example of a wooden construction product—a window frame—with a non-wood alternative made of polyvinyl chloride (PVC). This example examines the production and disposal phases of each window frame type, assuming a 35-year lifespan (Table 2.8.2 in (Hiraishi *et al.*, 2014)) before end-of-life treatment. To simplify, we omit substitution effects from waste incineration (as for all other CDR options, see section 4); otherwise, the example follows the system definition in Figure 2.11, where the soil carbon stock[33] change is allocated to hardwood and softwood based on their respective total biomass loss or gain per year. The primary aim of this example is to demonstrate the need for a consistent biogenic carbon accounting framework that includes forest dynamics, temporal storage, and future changes (as also stressed by (Strengers *et al.*, 2024)); thus, these adaptations do not alter the conclusions.

The forest model data for calculating the carbon budget of harvested wood are preliminary results from the Massimo model (Stadelmann *et al.*, 2019), which is also used in the context of quantifying "official" carbon stocks and flows in Swiss forests. Following (Head *et al.*, 2019; Buschbeck and Pauliuk, 2022), carbon stock changes (together with the actual carbon contained in the harvested wood) are attributed to harvested wood products (HWPs) exiting the forest each year – an assumption which can be challenged (Strengers *et al.*, 2024). This means the embodied carbon in harvested wood products fluctuates with carbon stock dynamics of the forest: if the forest carbon stock grows, the HWP embodied carbon is net negative (i.e., carbon or CO_2 is taken up by the forest and removed from the atmosphere), and vice versa (i.e., carbon is released and CO_2 is emitted by the forest to the atmosphere). This ensures that, at scale, the system's carbon balance is maintained.

For prospective modeling in this example, which is needed for example for end-of-life of wooden products (highlighted in yellow in Figure 2.11), we use premise (Sacchi *et al.*, 2022) to generate forward-looking versions of the ecoinvent v3.10 LCA database (Wernet *et al.*, 2016). We perform both a standard, "static" LCA and a time-explicit, dynamic LCA using the newly developed "bw_timex" algorithm (Müller et al., in preparation) for a 1 m² window frame over its lifecycle. In the time-explicit LCA, the window frame production, including harvest, occurs four years before installation, with end-of-life treatment and disposal 30 years post-installation, totaling a 34-year lifecycle. We consider four cases: wooden and plastic frames, each placed in 2025 and again in 2075, to illustrate the impact of the forest carbon stock dynamics on the life cycle impacts.

3.6.1 Static LCA Results

For the standard LCA, which excludes biogenic carbon dynamics under both the 0/0 and -1/+1 approaches (discussed in section 2.2.6), the climate impacts values (applying GWP100 factors) are 144 kg CO_2-eq for the wooden frame and 387 kg CO_2-eq for the plastic frame. While prospective LCA may consider technological changes in production and waste treatment for later life cycles, these figures only provide a partial picture, as detailed below.

3.6.2 Time-explicit LCA

In the time-explicit LCA, the timing of activities, emissions, and future technological changes and the associated climate impacts are explicitly considered. For instance, if an activity takes place in 2040, inventory data from a prospective 2040 database is used. While dynamic LCA results can be presented using a dynamic GWP indicator (Levasseur et al., 2010), this differs from standard GWP100, making direct comparison challenging. Therefore, we first present radiative forcing profiles in Watts/m² (from which GWP or dynamic GWP factors can be derived) over time. Figure 3.11 to Figure 3.14 illustrate

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[33] Note that the term "soil carbon stock" is used here for the total stock of dead organic carbon including dead wood and litter.

these profiles for the four cases, which show the individual components of each life cycle product system (harvested wood products, production, and end-of-life treatment) as well as their sum. Table 3.2 then presents the dynamic GWP results for the four cases for two different time horizons 100 and 500 years.

Table 3.2: Dynamic GWP (Levasseur et al., 2010) values for the lifecycles of a window frame for the four cases wood or plastic and installation in 2025 or 2075. The dynamic GWP values are provided for a time horizon of 100 and 500 years. Note that these values cannot directly be compared to the static (or usual) GWP values.

Life cycle	**Installation year**	**Dyn. GWP100 [kg CO_2-eq]**	**Dyn. GWP500 [kg CO_2-eq]**
Wooden window frame	2025	-106	-114
Wooden window frame	2075	-39	-46
Plastic window frame	2025	391	366
Plastic window frame	2075	382	360

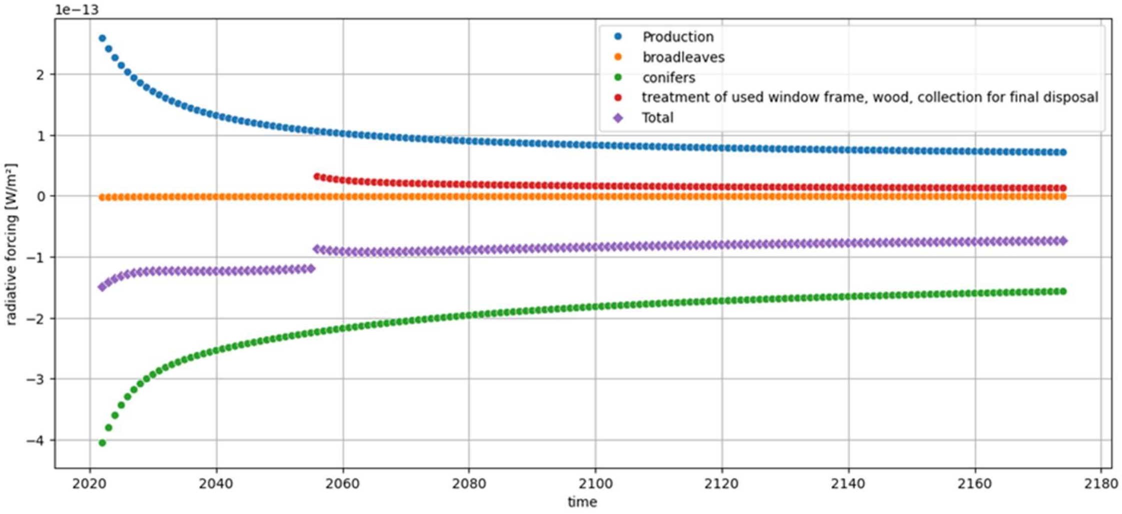

Figure 3.11: The radiative forcing profiles for the time explicit life cycle of a wooden window frame placed in 2025. Following (Levasseur et al., 2010), sequestered carbon is treated as a negative pulse emission.

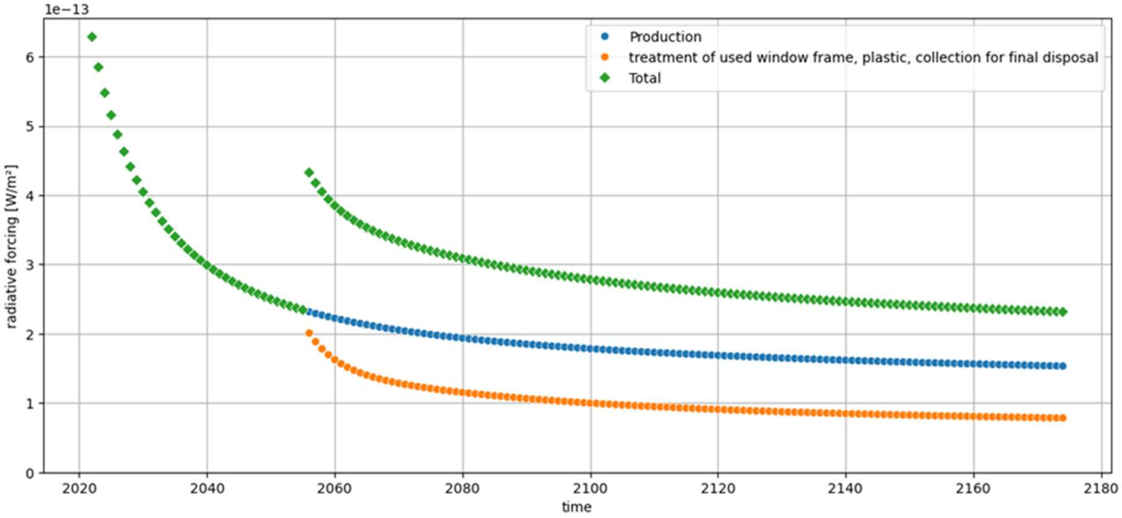

Figure 3.12: The radiative forcing profiles for the time explicit life cycle of a plastic window frame placed in 2025.

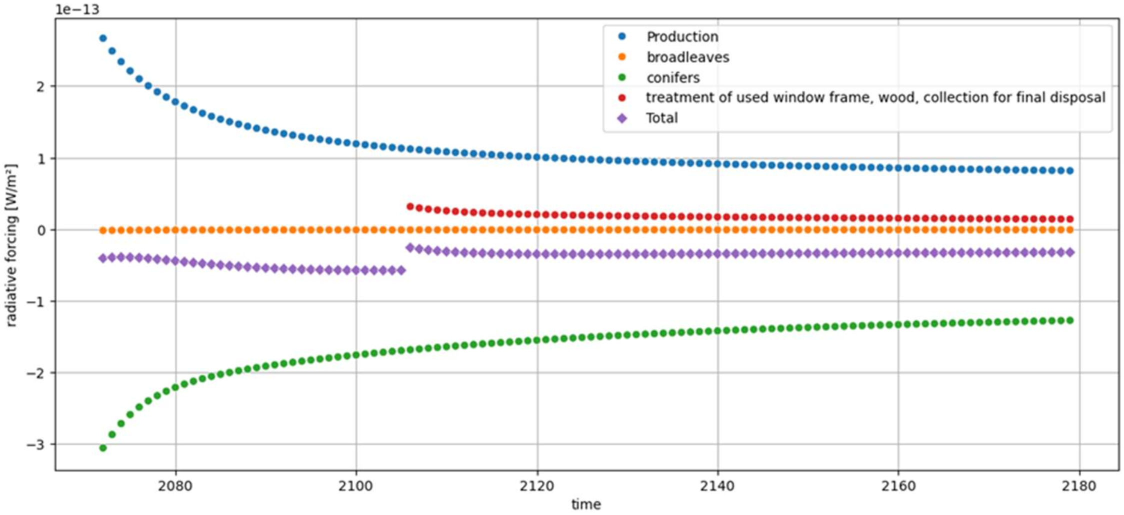

Figure 3.13: The radiative forcing profiles for the time explicit life cycle of a wooden window frame placed in 2075. Following (Levasseur et al., 2010), sequestered carbon is treated as a negative pulse emission.

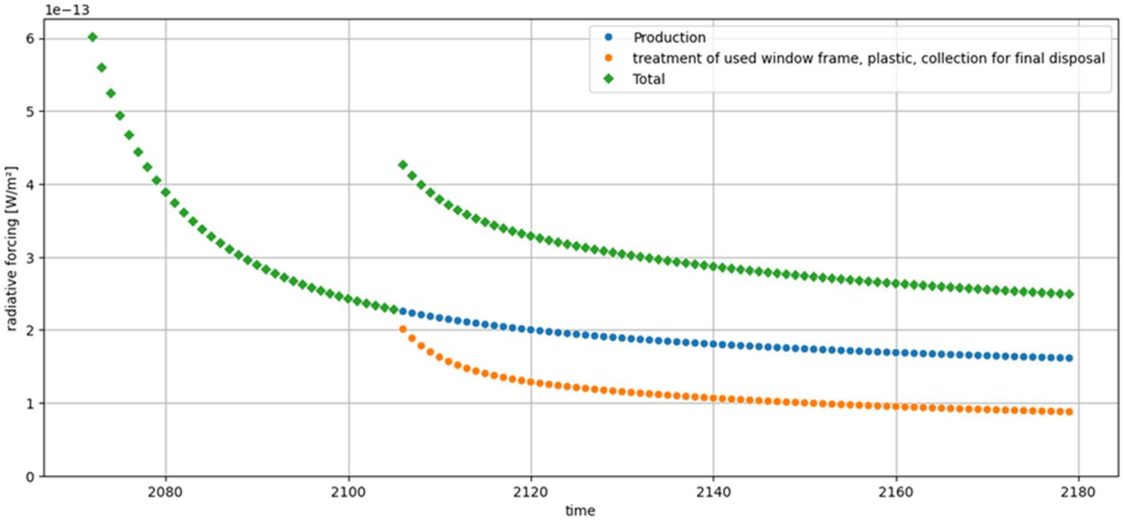

Figure 3.14: The radiative forcing profiles for the time explicit life cycle of a plastic window frame placed in 2075.

In 2021, four years before the installation of the 2025 wooden frame, the embodied carbon in HWP remains significant (Figure 3.11). However, by 2075, this is reduced due to lower net carbon stock change per harvested wood volume. In later years, or under different forest growth or management scenarios, this can even become a carbon burden. The 'net' embodied carbon of HWP or so-called ecosystem carbon cost (Head *et al.*, 2019) of harvests, depends on both the forest management, as well as the climate scenario and potential disruptive events. The Massimo forest inventory scenario used here is preliminary. However, scenarios in which the HWP carry a net carbon burden are not unlikely to occur.

For the plastic frame lifecycle, there is a slight decrease in radiative forcing between 2025 and 2075, attributed to the updated technology mix for the later year, which allows a less carbon intensive production of the plastic frame.

The same trends can be observed from the dynamic GWP vales in Table 3.2. We see that depending on which year the window frame is produced (or installed) the dynamic GWP for both time horizons changes drastically as a result of the forest carbon stock dynamics. For the plastic window frame, we observe a slight decrease in the dynamic GWP, as discussed above. We note here that this reduction might be stronger in alternative prospective scenarios. In this example, we used the business-as-usual scenario SSP2-Base from the Image Integrated Assessment Model, which projects a warming of 3 degree Celsius by the end of this century.

This example shows that a quantitative assessment of the climate impacts of using wood as a construction material is indeed a complex undertaking. It highlights the need to consider forest dynamics, as well as material lifecycles as well as the evolution of the decarbonizing economy. While this also requires impact metrics beyond the traditional GWP100, which include biogenic carbon and consider the timing of emissions, failing to do so will yield drastically different results. Moreover, while this example considers a small functional unit of the lifecycle of one window frame, when considering the use of wood as a construction material at large, scale effects such as substitution of other materials or energy carriers ad counterfactual scenarios need to be considered (Strengers *et al.*, 2024).

4 LCA tool for CDR methods

The purpose of the LCA tool for CDR methods developed within this project is threefold: First, it allows a comparison of the climate impacts and net CO_2 removal effectiveness of different CDR methods from a life cycle perspective in a user-friendly way by non-LCA experts, based on consistent data and assumptions. Second, the parameterized implementation of the LCA of different CDR methods in the tool (with parameters to be modified by users) provides a transparent documentation of our LCA models, including underlying calculations, assumptions, and data sources used. And third, the parameterization allows to explore a diverse set of parameter specifications representing different application settings and boundary conditions, making it easy to identify key parameters in the LCA and test their impact on results.

The tool – which is an excel file and can be downloaded[34] – contains the following CDR methods: DACCS, biochar-to-soil, wood as well as municipal waste combustion with CCS (as BECCS options), enhanced (coastal) weathering of rocks as well as ocean liming. Biochar-to-soil applications and BECCS generate energy (carriers) besides removing CO_2 from the atmosphere. In case of BECCS, heat and electricity generation can even be considered as the main purpose of biomass combustion. In the LCA tool and applying it for this report, we refrain from applying a system expansion approach and quantifying avoided GHG emissions (by substitution[35]) due to the subjectivity of choosing the replaced products, even if applying a system expansion and substitution concept would be the preferred way of dealing with multi-functionality in LCA of CDR (Duval-Dachary *et al.*, 2024). We only show GHG emissions generated and “negative GHG emissions”, which correspond on the one hand to the gross CO_2 removal from the atmosphere and on the other hand – with GHG emissions of the product system accounted for – to the net CO_2 removal. These results are provided for each of the CDR methods included, broken down into contributions from the main emission sources within the CDR product system. In addition, we report net CO_2 removal rates and generated amounts of energy wherever relevant. Thus, the LCA results shown here correspond to what has been recently introduced as “CDR accounting” by (Nordahl *et al.*, 2024). Such CDR accounting addresses a more focused question than LCA, namely: “Does a given process or project result in a net flux of greenhouse gases from the atmosphere when all of the relevant activities are accounted for?” (Nordahl *et al.*, 2024).

The tool allows to choose between employment of these CDR methods in four countries – Switzerland, Greece, Norway, and Iceland –, which were chose as they differ in terms of climate, composition of the energy system (fossil vs. renewable energy), and renewable yields, and which can be considered as representative for the variability of regional boundary conditions within Europe for the application of CDR. Further, first CDR and geological CO_2 storage implementations are ongoing in Norway and Iceland ad it seems relevant to represent those in our LCA calculations. In principle, this range of countries could be extended. The LCA settings in general represent current boundary conditions, corresponding to small-scale CDR employment as of today.

Background LCI correspond to ecoinvent v3.9.1 (Wernet *et al.*, 2016), system model “allocation, cut-off by classification” (ecoinvent, 2022). Climate impacts are quantified based on a time horizon of 100 years (“GWP100”) according to (IPCC, 2021), as implemented in the ecoinvent database. Results

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[34] https://www.psi.ch/de/ta/tools and https://www.suslab.ch/projects-1/life-cycle-assessment-of-carbon-dioxide-removal-options

[35] This is only relevant for CDR methods which generate useful products or services in addition to CO_2 removal. While for example DACCS “only” removes CO_2 from the atmosphere, biochar production often provides energy (heat and/or electricity) in addition to CO_2 removal and the same holds true for wood and waste combustion with CCS (one could also consider energy supply as their main purpose and CO_2 removal as by-product). In LCA, such activities with multiple valuable outputs can be dealt with by applying a system expansion and substitution approach, in which “by-products” substitute or replace their counterparts from default production routes and are assigned with “emission credits”. These emission credits correspond to the emissions which would be caused by default production routes and represent avoided, but not removed CO_2 (or GHG emissions), and must therefore always be shown separately (Terlouw, Bauer, *et al.*, 2021).

are shown for a functional unit of "One ton of CO_2 permanently[36] stored, i.e., removed from the atmosphere", often visualized as negative GHG emission. This functional unit corresponds to "One ton of gross CO_2 removal". The net amount of CO_2 removed is smaller and depends on life cycle GHG emissions, to be subtracted from the gross CO_2 removal.

The net CO_2 removal efficiency[37] of each CDR method is quantified as key outcome, calculated as:

$$\text{eff}_{\text{CO2-removal}} = (\text{gross } CO_2 \text{ removal} - \text{life cycle GHG emissions})/\text{gross } CO_2 \text{ removal}.$$

LCA results calculated with the tool and shown in the following do not necessarily aim at representing CDR only under Swiss conditions, but more generally also show the variability of LCA outcomes due to a broad range of boundary conditions.

4.1 Direct Air Carbon Capture and Storage (DACCS)

DACCS and LCA of DACCS in general are discussed in sections 2.2.1 and 3.1. The LCA integrated in the LCA tool builds upon few key data sources: Basic material and energy flows of DAC processes are based on (Terlouw, Treyer, *et al.*, 2021; Qiu *et al.*, 2022) and the impact of climate in terms of ambient temperature and humidity on low-temperature solid sorbent DAC performance is based on (Wiegner *et al.*, 2022). The impact of local climate on high-temperature DAC performance has not been considered due to lack of reliable data. Compression, transport and storage of CO_2 is modeled according to (Volkart, Bauer and Boulet, 2013; Terlouw, Treyer, *et al.*, 2021; Qiu *et al.*, 2022). The parameterization allows for selection of options and specifying the following parameters:

- Country of DAC operation: Switzerland, Greece, Norway, Iceland
- Location of CO_2 storage: Switzerland, Greece, Norway, Iceland
- DAC technology: low-temperature[38] (LT) solid sorbent or high-temperature[39] (HT) solvent CO_2 capture process
- Relative humidity and air temperature (for country average conditions) at the location of the DAC unit for LT solid sorbent DAC
- Source of electricity for DAC operation: country-specific average supply mix[40], wind power, geothermal power, coal power, natural gas power
- Heat source for DAC operation: waste incineration (i.e., waste heat), natural gas boiler[41], wood chips boiler
- Electricity source for CO_2 compression: country-specific mix, wind power, coal power, natural gas power
- Distance of CO_2 transport via pipeline[42]
- Depth of CO_2 storage
- Electricity source for CO_2 injection: country-specific mix, wind power, coal power, natural gas power

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[36] Permanent CO_2 removal corresponds to removal for 100 years and beyond in our accounting.

[37] We use "net CO_2 removal rate", "net GHG removal efficiency" and "carbon removal efficiency" as synonyms throughout this report.

[38] Corresponding to a temperature of around 100°C, which can be provided by many sources of waste heat and also industrial heat pumps.

[39] Corresponding to temperatures of several hundred degrees C, which can only be provided by combustion processes, e.g., natural gas or biomass boilers.

[40] From low voltage electricity markets.

[41] If heat for HT-DAC units is provided by natural gas combustion, the exhaust gases can be fed into the DAC unit, which prevents the CO_2 emissions of natural gas combustion to enter the atmosphere (Qiu *et al.*, 2022). Such a configuration would reduce climate impacts substantially but has not been implemented.

[42] Other means of CO_2 transport – for example in containers on lorries and ships or per railway – are possible but are uneconomic and therefore unlikely for large-scale CO_2 transport. Their environmental performance has been analyzed in (Burger *et al.*, 2024).

The average European electricity mix is used for CO_2 compression for trans-European CO_2 transport; for simplification, also within Switzerland[43]. The contribution analysis of greenhouse gases emitted differentiates between DAC unit infrastructure ("DAC plant"), DAC unit operation ("CO_2 capture"), CO_2 compression, CO_2 transport, and CO_2 storage.

4.1.1 Low-temperature (LT) solid sorbent DAC

Figure 4.1 shows life cycle climate impacts and net GHG removal, of the six LT DACCS configurations as specified in Table 4.1, each with the DAC unit operated in Switzerland.

Table 4.1: Six LT DACCS configurations used for visualization of GHG removal efficiency in Figure 4.1. NGCC: Natural Gas Combined Cycle; MSWI: Municipal Solid Waste Incineration (representative for any kind of excess or waste heat not used otherwise).

case	**DAC operation location**	**CO_2 storage location**	**CO_2 transport distance**	**electricity source for DAC operation**	**heat source for DAC operation**	**Electricity source for CO_2 storage**	**CO_2 injection depth**
1	Switzerland	Iceland	4000 km	CH grid	MSWI	geothermal	1000m
2		Iceland	4000 km	NGCC	NG combustion	NG turbine	3000m
3		Norway	2000 km	CH grid	MSWI	NO grid	1000m
4		Norway	2000 km	NGCC	NG combustion	NG turbine	3000m
5		Switzerland	10 km	CH grid	MSWI	CH grid	1000m
6		Switzerland	10 km	NGCC	NG combustion	NG turbine	3000m

In general, heat and electricity sources for DAC operation and their associated GHG emissions can be identified as mainly responsible for climate impacts, i.e., main drivers regarding the carbon removal efficiency. The transport distance for CO_2 via pipeline and the electricity source for CO_2 injection (for geological storage) is much less important. Transport distances for CO_2 via other means of transport, barge, train and especially lorry would be much more relevant as these transport options cause (substantially) higher GHG emissions (Burger *et al.*, 2024). DAC plant infrastructure related GHG emissions are negligible. Which means that from a Swiss perspective, capturing CO_2 domestically and permanently storing it abroad would be almost as effective in terms of CO_2 removal as domestic storage if CO_2 transport per pipeline without substantial CO_2 leakage can be ensured. However, the energy for operating the DAC units must be provided by additional low-carbon (renewable) resources to ensure high carbon removal efficiencies. Currently available CO_2 transport options such as trucks and barges, operated with fossil fuels, cause much higher transport related CO_2 emissions (Burger *et al.*, 2024).

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[43] The effect of this simplifying assumption on LCA results is negligible.

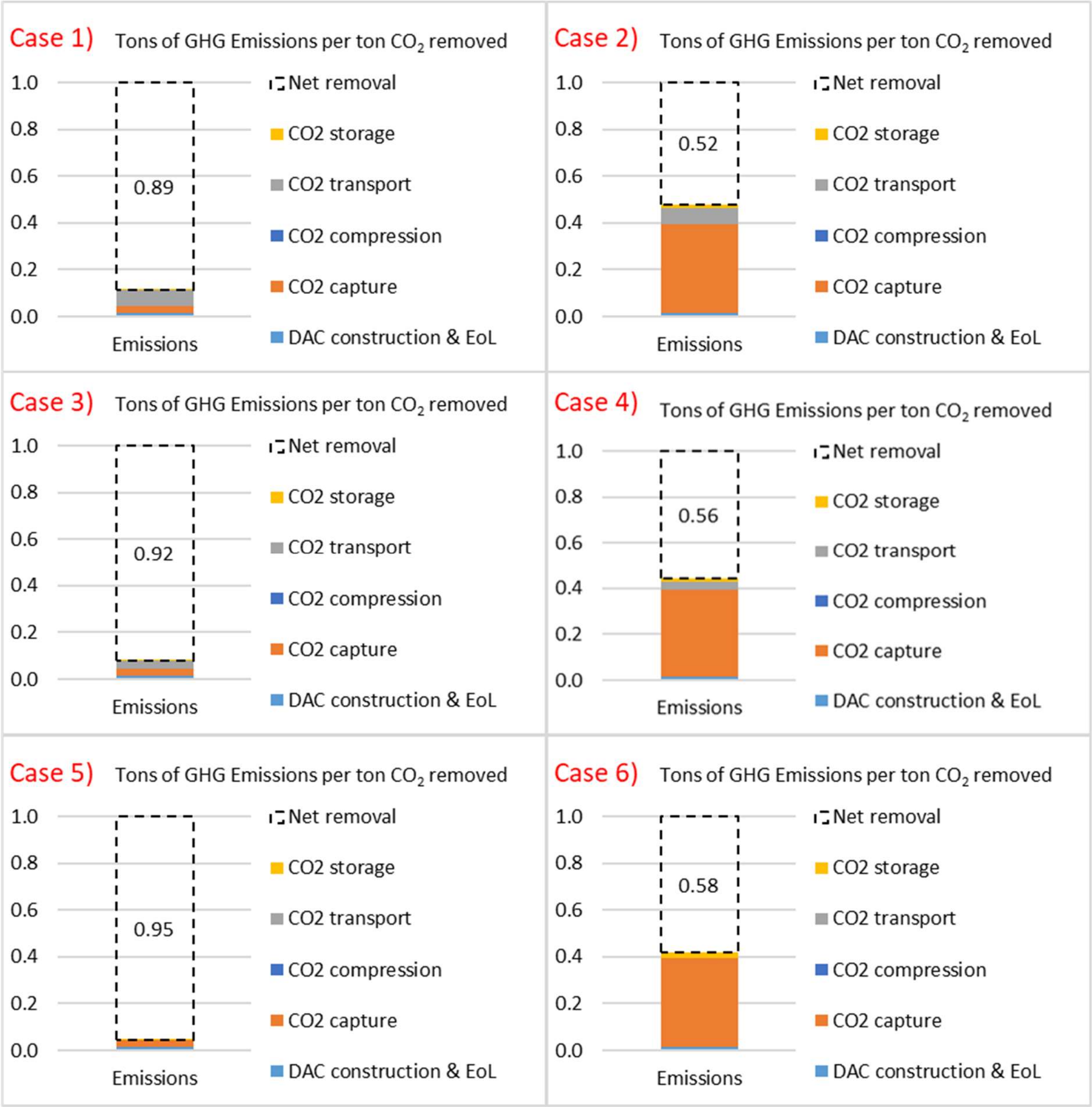

Figure 4.1: LCA results (climate impacts: tons of GHG emissions per ton of CO_2 permanently removed from the atmosphere) for different LT DACCS configurations with DAC operation in Switzerland, as generated with the LCA tool and specified above in Table 4.1. Location of CO_2 storage: Cases 1, 2: Iceland; cases 3, 4: Norway; cases 5, 6: Switzerland. Numbers in the dashed bar segments on top of the emissions indicate net CO_2 removal rates. Cases 2, 4, and 6 use natural gas as energy source for DAC operation.

Six further DACCS configurations with DAC operation abroad, for which climate impacts and net CO_2 removal rates are quantified and shown in Figure 4.2, are specified in Table 4.2.

These further cases show again the crucial importance of low-carbon energy supply for DAC operation. If (mainly) fossil energy carriers are used for heat and electricity supply, the associated GHG emissions can almost compensate the CO_2 removal by the DAC unit, as shown in case 12 – the electricity mix in Greece is dominated by coal power. Moreover, these cases also show the impact of the ambient climate at the location of the DAC operation on its energy consumption: comparatively warm and humid conditions increase the energy consumption of the DAC unit – DAC operated in Greece shows the highest energy consumption, the lowest can be observed in Iceland.

Table 4.2: Six LT DACCS configurations used for visualization of GHG emissions and CO_2 removal efficiency in Figure 4.2. NG: Natural Gas. IS: Iceland. CO_2 injection depth: 3000 m.

case	DAC operation location	CO_2 storage location	CO_2 transport distance	Electricity source for DAC operation	Heat source for DAC operation	electricity for CO_2 storage	CO_2 injection depth
7	Iceland	Iceland	10 km	geothermal	waste heat	geothermal	1000m
8	Iceland	Iceland	200 km	IS mix	NG combustion	NG turbine	3000m
9	Norway	Norway	10 km	NO mix	waste heat	NO mix	1000m
10	Norway	Norway	200 km	NO mix	NG combustion	NG turbine	3000m
11	Greece	Greece	10 km	onshore wind	waste heat	onshore wind	1000m
12	Greece	Iceland	6000 km	GR mix	NG combustion	NG turbine	3000m

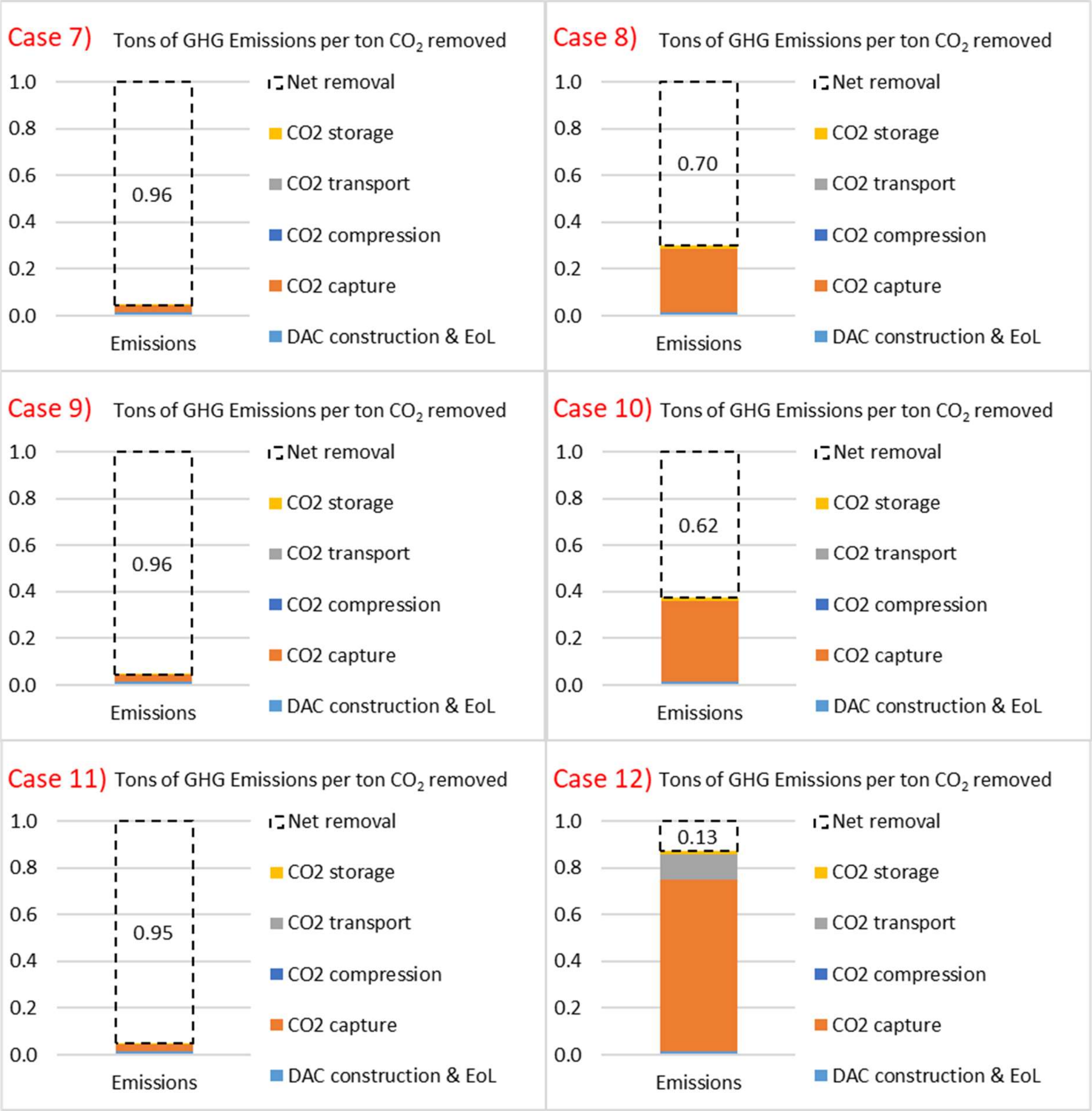

Figure 4.2: LCA results (climate impacts: tons of GHG emissions per ton of CO_2 permanently removed from the atmosphere) for different LT DACCS configurations with DAC operation in Iceland (cases 7, 8), Norway (cases 9, 10), and Greece (cases 11, 12), as generated with the LCA tool and specified above in Table 4.2. Location of CO_2 storage: Cases 7, 8, 12: Iceland; cases 9, 10: Norway; case 11: Greece. Numbers in the dashed bar segments on top of the emissions indicate net CO_2 removal rates. Cases 8, 10, and 12 use natural gas as heat source for DAC operation.

4.1.2 High-temperature (HT) solvent DAC

Figure 4.3 shows life cycle climate impacts and net GHG removal, of the six HT DACCS configurations as specified in Table 4.3. The use of waste heat for low-carbon heat supply for DAC operation is less of an option compared to LT DAC units, as usually, waste heat is not available at the temperature level needed for HT DAC[44]. CO_2 emissions from the heat source (e.g., natural gas combustion) are not assumed to be fed back into the DAC unit but released to the atmosphere. Low carbon alternatives to natural gas for heat supply are in general wood or other solid biomass, but also biomethane combustion. We include wood combustion as an option in our LCA tool.

Table 4.3: Six HT DACCS configurations used for visualization of GHG emissions and CO_2 removal efficiency in Figure 4.3. NGCC: Natural Gas Combined Cycle. CO_2 injection depth: 3000 m.

case	**DAC operation location**	**CO_2 storage location**	**CO_2 transport distance**	**electricity source for DAC operation**	**heat source for DAC operation**	**electricity source for CO_2 storage**
1	Switzerland	Iceland	4000 km	CH grid	wood combustion	geothermal
2	Switzerland	Switzerland	10 km	NGCC	NG combustion	NG turbine
3	Norway	Norway	10 km	NO mix	wood combustion	NO mix
4	Norway	Norway	200 km	NO mix	NG combustion	NG turbine
5	Iceland	Iceland	10 km	geothermal	wood combustion	geothermal
6	Iceland	Iceland	200 km	IS mix	NG combustion	NG turbine

Like the LT DAC, the energy sources used for DAC operation are the key drivers regarding the climate impacts generated and thus the carbon removal effectiveness. DAC infrastructure, CO_2 transport, and injection are of minor importance. As energy carriers for heat supply are needed which allow for temperatures of several hundred degrees Celsius, waste heat sources are not an option. Besides wood (or other types of biomass which can be burned), synthetic methane and hydrogen could be used to generate high-temperature heat. However, these energy carriers are likely to be needed for other purposes and therefore not considered here. An alternative would be to feed the exhaust gases of heat supply combustion processes into the DAC unit and store these CO_2 emissions. This seems to be possible, but increases the need for CO_2 storage volumes substantially, i.e. by about a third (Qiu *et al.*, 2022).

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[44] (between 300 °C and 900 °C), https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture (8.12.2024).

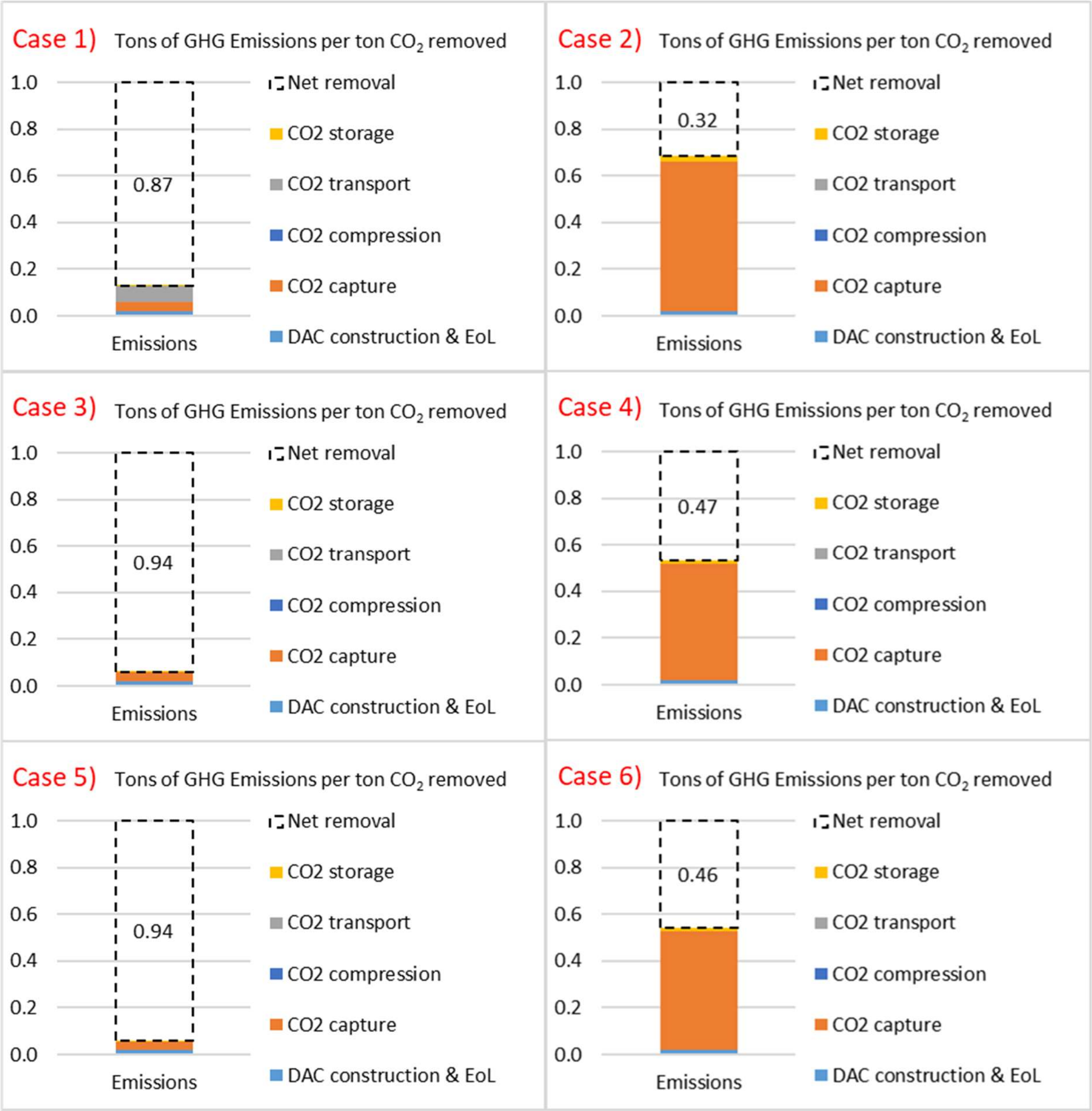

Figure 4.3: LCA results (climate impacts: tons of GHG emissions per ton of CO_2 permanently removed from the atmosphere) for different HT DACCS configurations with DAC operation in Switzerland (cases 1, 2), Norway (cases 3, 4), and Iceland (cases 5, 6), as generated with the LCA tool and specified above in Table 4.3. Location of CO_2 storage: Cases 1, 5, 6: Iceland; cases 3, 4: Norway; case 2: Switzerland. Numbers in the dashed bar segments above the emissions indicate net CO_2 removal rates. Cases 2, 4, and 6 use natural gas as high-temperature heat source for DAC operation.

4.2 Biochar-to-soil applications

The aforementioned LCA of biochar-to-soil applications (Hoeskuldsdottir, 2022) (section 3.2) has been used as main data source for the implementation of biochar-to-soil application as CDR method in the LCA tool. This LCA represents a slow pyrolysis process for biochar production, which also generates synthesis gas and bio-oil (or tar), using dry ("woody") natural biomass as feedstock. In our analysis, "permanently" stored CO_2, i.e., CO_2 permanently removed from the atmosphere, corresponds to the amount of carbon, which is still present in the biochar applied and the soil, respectively, after hundred years[45]. Calculations are based on a biochar application rate of 1 ton per hectare and year.

The implemented parameterization allows for selection of options and specifying the following parameters:

- Country of implementation: Switzerland, Greece, Norway, Iceland
- Amount of annually converted fresh biomass (default: 10'000 tons per year)
- Tree species: spruce, oak, pine, birch, and beech; they differ in terms of elementary composition and humidity
- Biomass origin
- Whether or not synthesis gas and bio-oil are converted into heat and electricity (in a CHP), which can be used for drying the biomass feedstock and operating the pyrolysis process
- Whether or not biochar application leads to a reduction of fertilizer use (default setting: no reduction, as assumed to be representative for Switzerland (BAFU, 2023))
- Moisture content of the biomass before technical drying (biomass is assumed to enter pyrolysis at a moisture content of 10%)
- Means of transport and transport distance for biomass transport before entering the pyrolysis process
- Pyrolysis temperature
- Sources of heat and electricity for biomass drying and pyrolysis operation in case synthesis gas and bio-oil are not used for these processes
- Average soil temperature per country is considered via the country choice for biochar application

The interdependencies between parameters (Table 3.1) are – as far as possible and relevant for the outcomes of the LCA – considered in the automated calculation of LCA results. All underlying assumptions, calculations and data sources used are provided and discussed in (Hoeskuldsdottir, 2022). Aspects not addressed here – for reasons explained in section 3.2 – are for example potential changes in albedo due to biochar application, potential changes in N_2O emissions of the soil, and potential impacts on crop yields, soil properties, etc. Long-term experiences in some of these contexts are still missing in Switzerland (BAFU, 2023).

Based on specific parameter settings, generated life cycle GHG emissions and CO_2 removed from the atmosphere ("negative" GHG emissions) are calculated as well as the net CO_2 removal efficiency and the net electricity and heat production available due to conversion of syngas and bio-oil into heat and electricity in a CHP unit after their potential use for biomass drying and pyrolysis operation. Greenhouse gases emitted are split into contributions from forestry and harvesting activities ("biomass"), biomass drying, biomass transport, biochar transport, and pyrolysis plant infrastructure ("pyrolysis"). We refrain from applying a substitution concept to quantify avoided emissions due to the heat and power generation from the available syngas and bio-oil. Instead, we provide the quantities of net heat and power generation converting these two by-products into heat and electricity in a CHP unit (Table 4.5 and Table 4.13).

Figure 4.4 shows exemplary results for six different biochar-to-soil configurations, each for a conversion of 10'000 tons of fresh biomass per year, biochar application in Switzerland, without

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[45] Most recent findings by (Brunner, Hausfather and Knutti, 2024) show that a removal period of 100 years is by far not equivalent to permanent CO_2 removal in terms of climate impacts. However, we were not able to consider this in our quantitative analysis, as these results were published during the last revision of this report.

reduction in fertilizer use or any impact on crop yields and N_2O emissions and otherwise as specified in Table 4.4.

Important to note is that “permanently removed CO_2” corresponds to the amount of carbon still present in the biochar applied to soil after 100 years.

Two major effects can be observed based on these examples: First, biomass (and biochar) transport over long distances causes substantial GHG emissions (cases 3, 6), which reduce the net-effectiveness of biochar in a way which should be avoided; second, it can also be observed that the use of wet biomass, e.g., wood directly from the forest with a high moisture content, should be avoided, as this substantially increases the energy demand for technical drying and thus reduces the amount of energy from the pyrolysis process available for external users. And further, using fossil energy carriers for biomass drying increases the GHG emissions substantially (case 4). The reason why biomass transport for biochar application is that much more relevant in terms of GHG emissions compared to BECCS (i.e., the wood power plant with CCS) is the comparatively much lower fraction of biogenic carbon in the biomass permanently removed from the atmosphere by biochar-to-soil application as the majority is ultimately released due to combustion of the pyrolysis by-products, but also by decomposition of biochar.

Table 4.4: Specification of six biochar-to-soil applications in Switzerland for visualization of life cycle GHG emissions and net GHG removal in Figure 4.4. Biochar transport in each case: 50 km per lorry, 10 km per tractor.

case	**Biomass type**	**Biomass origin**	**Location of pyrolysis**	**Biomass transport**	**Moisture content of biomass after road drying[46]**	**Biomass drying before/after transport**	**Energy source for biomass drying**	**Energy source for pyrolysis plant**	**Pyrolysis temperature**
1	Spruce	Switzerland	Switzerland	Lorry: 100km	30%	after	pyrolysis by-products	pyrolysis by-products	600°C
2	Spruce	Switzerland		Lorry: 300km	50%	after	pyrolysis by-products		600°C
3	Spruce	Greece		Lorry: 300km Freight ship: 1000km	30%	before	natural gas		400°C
4	Beech	Switzerland		Lorry: 100km	30%	after	pyrolysis by-products		600°C
5	Beech	Switzerland		Lorry: 300km	50%	after	pyrolysis by-products		600°C
6	Beech	Greece		Lorry: 300km Freight ship: 1000km	30%	before	wood		400°C

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[46] “road drying” reflects common practice in forestry to store harvested wood next to forest roads for a first period of time in which the natural humidity of the wood is reduced without external energy consumption.

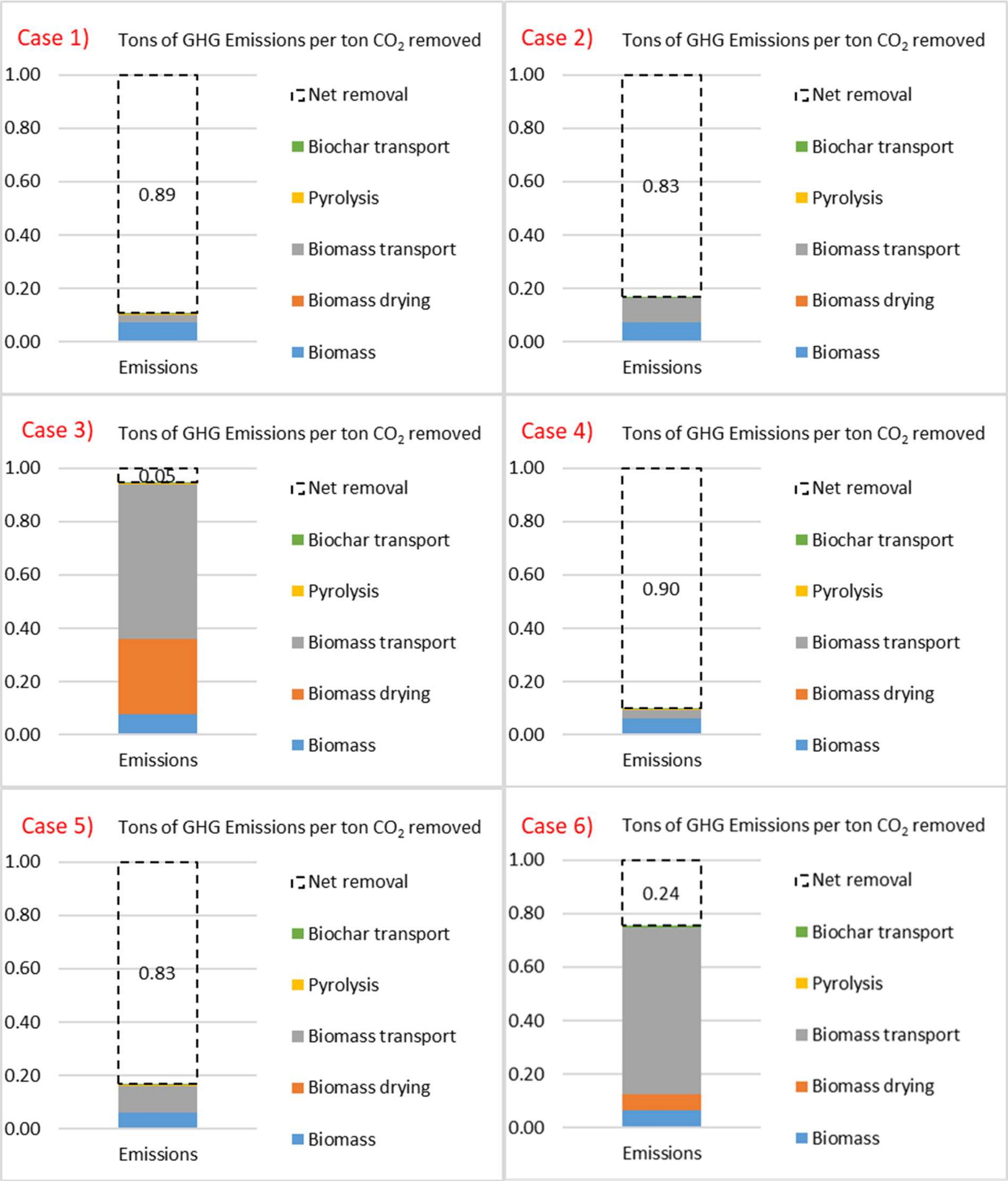

Figure 4.4: LCA results (climate impacts: tons of GHG emissions per ton of CO_2 permanently removed from the atmosphere) for different biochar-to-soil configurations, as generated with the LCA tool and specified in Table 4.4. Numbers in the dashed bar segments on top of the emissions indicate net CO_2 removal rates. Biochar production and application in Switzerland in all cases. Long-distance wood import assumed in cases 3 and 6.

Table 4.5 provides an overview of the key outcomes analysing the six cases of biochar-to-soil applications as specified in Table 4.4. Net CO_2 removal rates for all cases using domestic biomass are high, within a range of 83-90%. Cases 3 and 6 show net CO_2 removal rates of only 5% and 24%, mostly due to fossil energy consumption for biomass drying ad transport. The effect of tree species shows in the energy output: cases 4-6 using beech provide slightly higher amounts of energy than cases 1-3 using spruce. As in cases 3 and 6 external energy is used for wood drying before transport, higher amounts of energy from the pyrolysis process remain available to external users. Cases 2 and 5 need comparatively more energy from the pyrolysis process for wood drying, as the feedstock comes with a moisture content of 50% as opposed to the 30% in the other cases and thus. Less is available for external users.

Table 4.5: Overview of the key outcomes analyzing the energy performance of the six different biochar cases specified in Table 4.4.

Key outcomes		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
CO_2 Removal	Removal efficiency	89%	83%	5%	90%	83%	24%
	Net CO2 removed (tCO2e)	0.89	0.83	0.05	0.90	0.83	0.24
Energy output	Electricity (MWh)	0.94	0.89	0.99	1.07	1.02	1.11
	Electricity / t biomass (MWh/dry t)	0.47	0.44	0.50	0.54	0.51	0.56
	Heat (GJ)	4.8	0.8	8.8	5.7	1.3	9.9
Biomass	Biomass utilized (wet t)	7.4	7.4	8.3	8.1	8.1	8.9
	Carbon removal rate from biomass	38%	38%	33%	35%	35%	32%

4.3 Wood and waste combustion with Carbon Capture and Storage (BECCS)

4.3.1 Wood power plant with CCS

A generic biomass power plant burning natural[47] wood chips with a CO_2 capture rate of 90% and modelled according to (Volkart, Bauer and Boulet, 2013) represents one of the two BECCS options in focus of this work. A lifetime of 25 years at 5500 annual full load hours has been assumed. Electrical efficiency of the power plant without CO_2 capture would be 30%, with CO_2 capture it drops to 20%. A small fraction of this efficiency drop is due to electricity supply for CO_2 compression before transport. Transport and final storage of CO_2 is modelled according to (Terlouw, Treyer, *et al.*, 2021), the same way as for DACCS. The average European electricity mix is used for CO_2 compression for trans-European CO_2 transport; for simplification, also within Switzerland.

This BECCS LCA in our LCA tool is simplified in the sense that it is based on the assumption that (excluding the CCS part of the product system) our "forest-bioenergy" system is carbon neutral, i.e., that the CO_2 emissions from wood combustion are equal to the net CO_2 uptake of the forest. This aspect is further discussed in section 3.3. We refer to (Strengers *et al.*, 2024) for a very extensive and insightful discussion of the topic of biogenic carbon flows in the context of bioenergy and the resulting climate impacts, which is also related to biochar systems using forest biomass and the use of wood as construction material.

For comparing this BECCS options with the other CDR methods included in the LCA tool (using the common functional unit of one gross ton of CO_2 removed), it has been assumed that permanent CO_2 removal represents the main service of the wood power plant with CCS, and electricity production is considered as "burden-free by-product". This is a subjective choice, which depends on the question(s) to be answered and can be challenged. System expansion – quantifying environmental burdens of a "basket of products", in this case electricity production and CO_2 removal – would be an alternative, which, however, does not allow to quantify "product-specific" environmental burdens of the CO_2 removal service. These are required for comparing different CDR options in a meaningful way. Here, we refrain from quantifying avoided environmental burdens applying a substitution approach as strongly suggested by the commissioner of this work, which would require subjective choices regarding substituted products and services. Instead, we only quantify the electricity generated

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[47] As opposed to waste wood combustion.

besides CO_2 removal and compare this energy output to the other BECCS option, namely MSWI (see section 4.3.2). From an LCA perspective, this choice or approach represents a "worst case" for the CDR service provided.

The implemented parameterization allows for selection of options and specifying the following parameters:

- Country of power plant operation and biomass origin: Switzerland, Greece, Iceland, and Norway
- Tree species: spruce, oak, pine, birch, and beech; they differ in terms of elementary composition and humidity
- Moisture content of the biomass after roadside drying, which determines the amount of energy needed for further drying – wood enters the combustion with a moisture content of 10%
- Energy sources for drying the wood before entering the combustion: Heat and electricity can be provided internally by the wood combustion plant, or by external fossil and renewable sources
- Vehicle(s) for wood transport: truck, container ship, freight train
- Wood transport distances per vehicle
- Location of CO_2 storage[48]: Switzerland, Greece, Norway, Iceland
- Electricity sources for CO_2 storage: country-specific mix, wind power, coal power, natural gas power, geothermal power
- Distance for CO_2 transport via pipeline[49]
- Depth of CO_2 storage

Based on specific parameter settings, generated life cycle GHG emissions, electricity and heat consumption as well as net electricity production and net GHG removal from the atmosphere are calculated. Greenhouse gases emitted are split into contributions from forestry and harvesting activities ("biomass"), biomass drying, biomass transport, contributions from CO_2 capture (e.g., MEA consumption), CO_2 transport, and CO_2 storage. Further, the remaining CO_2 emissions at the power plant due to the CO_2 capture rate below 100% are tracked – as these are of biogenic origin and biomass is assumed to be harvested in sustainable ways, these CO_2 emissions are assumed to have zero impact on climate change.

Figure 4.5 shows exemplary results for six different BECCS configurations for power plant operation in Switzerland, as specified in Table 4.6. We limit the choice of wood types here to spruce and beech, typical soft- and hardwood species harvested in Switzerland, and Europe, in general. Overall, as long as wood from European forests under sustainable harvesting conditions (i.e., harvest rates do not exceed natural regrowth of biomass, as assumed in this work) is used, the tree species as such has only very minor impact on the climate effectiveness of BECCS, as elementary compositions are similar, and land-use related climate impacts can be assumed to be zero. Main factors determining the net carbon removal rates of the BECCS systems specified are biomass and CO_2 transport distances. The shorter both are, the higher the net carbon removal rates. Thus, using Swiss biomass is of advantage and storing CO_2 in Switzerland would also be. However, even transporting both wood and CO_2 over long distances within Europe does not completely compromise the climate effectiveness of BECCS, as the net carbon removal rate for case 3) still amounts to 80%. Lower moisture contents of wood

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[48] Either in saline aquifers or depleted oil and gas fields.

[49] Other means of CO_2 transport – for example in containers on lorries and ships or per railway – are possible but are uneconomic and therefore unlikely for large-scale CO_2 transport.

entering the combustion results in higher net power generation, as less energy from the wood combustion is needed for wood drying and can be turned into electricity.

Table 4.6: Specification of six exemplary cases of wood combustion with CCS, power plant operated in Switzerland, for visualization of life cycle GHG emissions and net CO_2 removal in Figure 4.5. Biomass drying: at power plant with internally available energy (reducing the net electricity output); CO_2 injection depth: 3000 meters.

case	**Wood power plant operation**	**Type of wood**	**Origin of wood**	**Energy for wood drying**	**Means of wood transport and distance**	**Wood moisture after roadside drying**	**CO_2 storage location**	**CO_2 transport distance**	**CO_2 injection depth**
1	Switzerland	Spruce	Switzerland	Internal	Lorry: 50km	40%	Switzerland	50km	1000m
2		Beech	Switzerland	Internal	Lorry: 200km Freight train: 300km	40%	Switzerland	300km	3000m
3		Spruce	Overseas	Internal	Lorry: 1000km Freight ship: 6000km	40%	Switzerland	300km	3000m
4		Spruce	Switzerland	Internal	Lorry: 50km	40%	Iceland	4000km	3000m
5		Beech	Switzerland	Internal	Lorry: 200km Freight train: 300km	50%	Iceland	4000km	3000m
6		Spruce	Greece	Natural gas	Lorry: 1000km Freight train: 3000km	50% (drying before transport)	Iceland	4000km	3000m

We refrain from showing options for wood drying other than using energy from the wood combustion in Switzerland itself, as from the perspective of operating wood power plants with CCS in Switzerland, using fossil energy sources for that purpose seems unrealistic. Average grid electricity is used per default for CO_2 injection in Switzerland and Iceland, respectively.

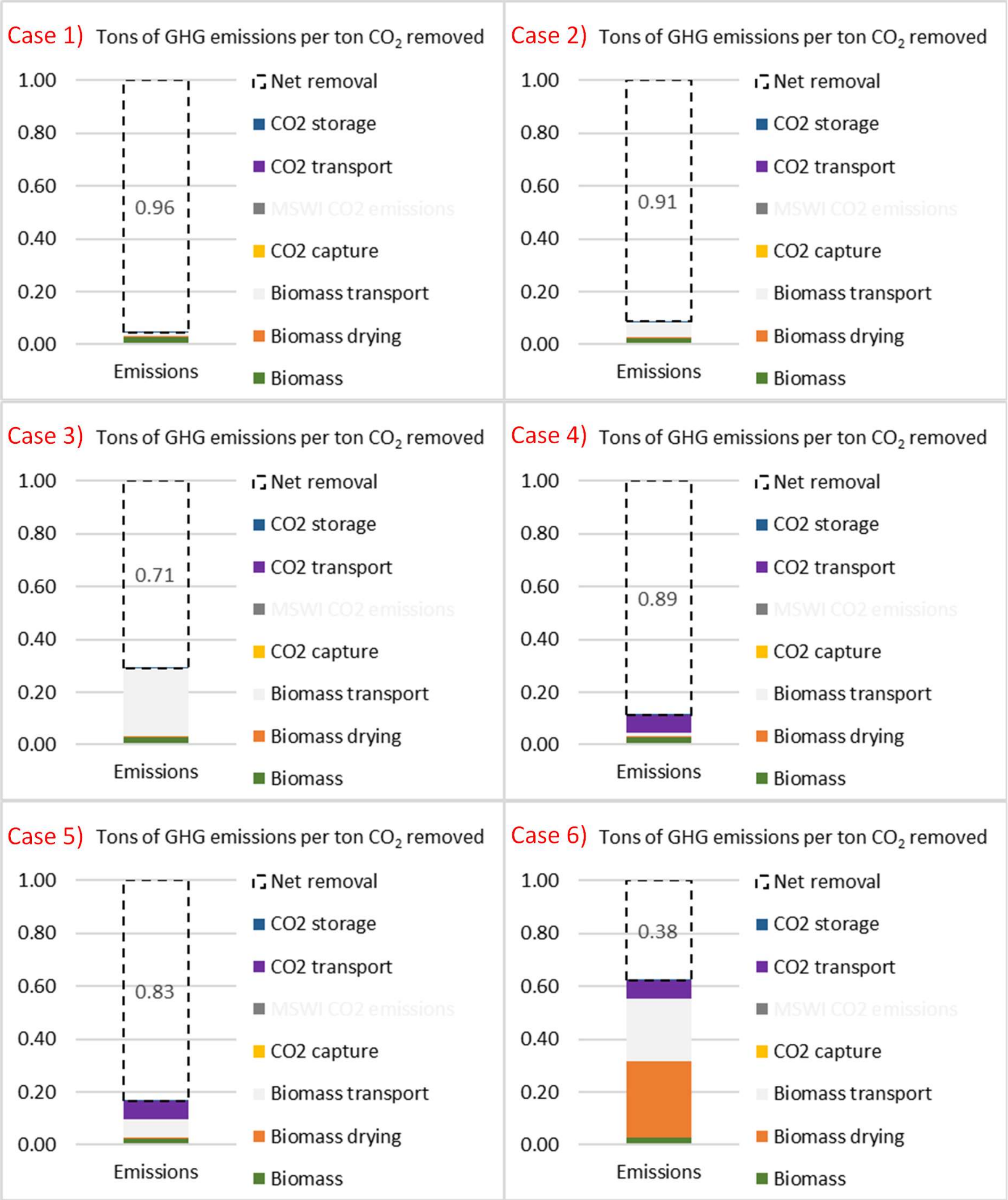

Figure 4.5: LCA results (climate impacts: tons of GHG emissions per ton of CO_2 permanently removed from the atmosphere) for different BECCS configurations (wood combustion with CCS), as generated with the LCA tool and specified in Table 4.6. Numbers in the dashed bar segments on top of the emissions indicate net CO_2 removal rates. Wood power plant operation in Switzerland in all cases; CO_2 storage in Switzerland (cases 1-3) and Iceland (cases 4-6).

Results show that if wood is sourced locally in Switzerland and CO_2 can be stored in proximity, net CO_2 removal rates close to 100% are feasible (case 1). Wood transport distances should be minimized, as cases 3 and 6, where wood is imported from overseas and Greece, respectively, show considerable GHG emissions due to transport activities. Results are much less sensitive regarding CO_2 transport, as shown in cases 4-6, in which CO_2 is assumed to be stored in Iceland. Biomass drying using fossil energy sources should also be avoided in the interest of achieving high net CO_2 removal rates (case 6).

Table 4.7 summarizes key outcomes of the analysis of wood power plants with CCS. While net CO_2 removal factors substantially differ, key outcomes in terms of energetic performance of all six cases analysed are very similar. Case 6 generates slightly more electricity, as external energy is assumed to be used for wood drying before long-distance transport. This slightly higher power generation does, however, not compensate for the very low net CO_2 removal effectiveness, which is due to long-distance wood transport and the use of natural gas for wood drying.

Table 4.7: Key outcomes from the analysis of wood combustion with CCS for the six cases specified in Table 4.6.

Key outcomes		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
CO_2 removal	Removal efficiency	96%	91%	71%	89%	83%	38%
	Net CO_2 removed (t CO_2e)	0.96	0.91	0.71	0.89	0.83	0.38
Energy output	Electricity (MWh)	0.48	0.47	0.48	0.48	0.46	0.52
	Electricity / t biomass (MWh/dry t)	0.79	0.75	0.79	0.79	0.74	0.84
	Heat (GJ)	0.0	0.0	0.0	0.0	0.0	0.0
Biomass	Biomass utilized (wet t)	3.08	3.12	3.08	3.08	3.12	3.08
	CO2 capture rate from biomass	90%	90%	90%	90%	90%	90%
	Energy efficiency from biomass	15%	15%	15%	15%	15%	16%

4.3.2 Municipal solid waste incineration (MSWI) with CCS

The MSWI plant operation with CO_2 capture is modelled according to (Bisinella *et al.*, 2021). We represent two plant configurations, one of which only generates electricity as useful product, the other one both heat and electricity[50]. As of today, Swiss MSWI all provide heat and electricity as useful outputs, supplying electricity to the grid and heat to industrial users or district heat networks (Rytec AG, 2024). The CO_2 capture rate of both WSWI configurations in our LCA model is 85%[51]. The "electricity only" configuration without CO_2 capture would exhibit an electric net efficiency of 27%, with CO_2 capture it amounts to 20%. The combined heat and power (CHP) configuration without CCS would exhibit electrical and thermal net efficiencies of 23% and 62%, respectively, while the CHP configuration with CCS exhibits electrical and thermal net efficiencies of 14% and 75%, respectively. An increasing thermal efficiency due to CCS seems counterintuitive, but a large fraction of the electricity needed for CO_2 capture can be recovered as low-temperature heat fed into district heating networks (Bisinella *et al.*, 2021). Energy for CO_2 capture is provided internally by the MSWI plant reducing the net electricity production. The fraction of biogenic carbon in the waste is set to 52% corresponding to the average share of biogenic carbon in municipal waste in Switzerland in 2022 (BAFU, 2024). Electricity for CO_2 compression at the MSWI plant is provided by the MSWI plant, reducing its net electricity generation. Transport and final storage of CO_2 is modelled according to (Terlouw, Treyer, *et al.*, 2021), the same way as for DACCS. Simplifying the modelling of CO_2 transport, average European electricity is assumed as energy source for pipeline CO_2 transport in general.

The fraction of biogenic carbon in the municipal solid waste is an important parameter, as it determines the shares of biogenic CO_2 removed versus fossil CO_2 emissions avoided (capturing and permanently storing CO_2 from fossil sources corresponds to emission reduction or avoidance, not CO_2 removal) and the climate impact of the residual CO_2 emissions, which are not captured by the CO_2 capture unit. Further, it determines the denominator for assigning downstream GHG emissions due

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[50] In Switzerland, MSWI plants are currently operated in various ways, either primarily generating electricity, or – being connected to a district heating network – primarily heat (especially in winter) (Otgonbayar and Mazzotti, 2024).

[51] In general, higher CO_2 capture rates are possible (Otgonbayar and Mazzotti, 2024), which would increase the carbon removal MSWI with CCS can generate. However, the study we rely on for performing the LCA uses 85% per default (Bisinella *et al.*, 2021). Changing this capture rate would require recalculating the energy balance of the MSWI plant and perform process engineering type of analysis, which is out of scope of this work.

to CO_2 transport and storage to the functional unit of one gross ton of CO_2 removed. Because the feedstock used is waste and the main purpose of waste incineration can be assumed to be waste treatment, upstream environmental burdens are assumed to be zero in line with common practice in LCA.

As for the wood combustion plant, we refrain also for the MSWI plant from quantifying avoided GHG emissions applying a substitution approach for the generated electricity and heat. Instead, we report the net amounts of power and heat generation. An LCA comparing MSWI without and with CCS, respectively, would have to consider the reduced output of useful energy of the MSWI plant with CO_2 capture, i.e., quantify the environmental burdens due to the fact that this "missing" heat and power generation would have to be provided by other sources. This is, however, out of scope of this work, as it would require a system perspective in terms of Swiss energy supply.

Users of the LCA tool can adjust the following parameters:

- Country of MSWI operation: Switzerland, Norway, Iceland, and Greece
- Location of CO_2 storage: Switzerland, Norway, Iceland, and Greece
- CO_2 transport distance (via pipeline)
- CO_2 injection depth
- Source of electricity for CO_2 injection and storage: country-specific grid mix, natural gas turbine, geothermal power
- Fraction of biogenic carbon content of the waste (and thus biogenic and fossil CO_2 emissions)
- Allocation of downstream emissions: either 100% to CO_2 removal or according to the biogenic carbon fraction

We refrain from using the tool to analyse MSWI plants in other countries than Switzerland, as from a Swiss CDR perspective, using domestic MSWI plants with CCS is of primary interest. We show the effect of assigning residual fossil CO_2 (not captured by the CO_2 capture unit) as well as downstream emissions (those related to CO_2 transport and storage) either entirely to the CO_2 removal service of the MSWI with CCS (i.e., the biogenic CO_2) or according to the biogenic carbon fraction of the waste. Per default (Figure 0.1, Figure 4.6 and Figure 4.10) and if not explicitly highlighted, residual fossil CO_2 and downstream emissions are assigned to CO_2 removal, as CDR is the focus of our analysis. This is, however, an arbitrary choice, which depends on the context and the question to be answered. Overall, adding CCS to MSWI also reduces fossil CO_2 emissions. Figure 4.6 shows exemplary results for six different MSWI configurations for MSWI operation in Switzerland, as specified in Table 4.8.

Table 4.8: Specification of cases for quantifying GHG emissions and net CO_2 removal rates of the MSWI plant with CCS. CO_2 storage depth: 3000 meters. Residual fossil CO_2 (not captured by the CO_2 capture unit) and downstream emissions are entirely assigned to CO_2 removal.

case	**MSWI configuration**	**MSWI plant operation**	**Biogenic carbon fraction in the waste**	**CO_2 storage location**	**Electricity source for CO_2 storage**	**CO_2 transport distance**	**CO_2 injection depth**
1	CHP	Switzerland	52%	Switzerland	country mix	100km	1000m
2	CHP			Switzerland	country mix	300km	2000m
3	Electricity only			Switzerland	natural gas turbine	500km	3000m
4	CHP			Iceland	country mix	4000km	1000m
5	CHP			Iceland	geothermal	4000km	2000m
6	Electricity only			Iceland	natural gas turbine	4000km	3000m

The results in Figure 4.6 reveal that domestic CO_2 storage would be an advantage regarding indirect GHG emissions, as carbon removal efficiencies of MSWI with CCS with CO_2 storage in Switzerland are about 10%-points higher than with CO_2 storage in Iceland. Using electricity from fossil sources for CO_2 storage only slightly reduces the carbon removal efficiencies.

Parameters are kept constant here, but parameters with a potentially considerable effect on carbon removal efficiencies are the biogenic carbon fraction in the waste and the CO_2 capture rate at the waste incinerator. The higher the biogenic carbon content, the lower the residual fossil CO_2 emissions due to CO_2 capture rates below 100%. The same holds true for increasing CO_2 capture rates: less fossil CO_2 is emitted, and more biogenic CO_2 captured contributes to CDR. Whether the MSWI generates heat and electricity ("CHP configuration"), or only electricity, does not affect the results regarding the CDR service provided, only the energy outputs.

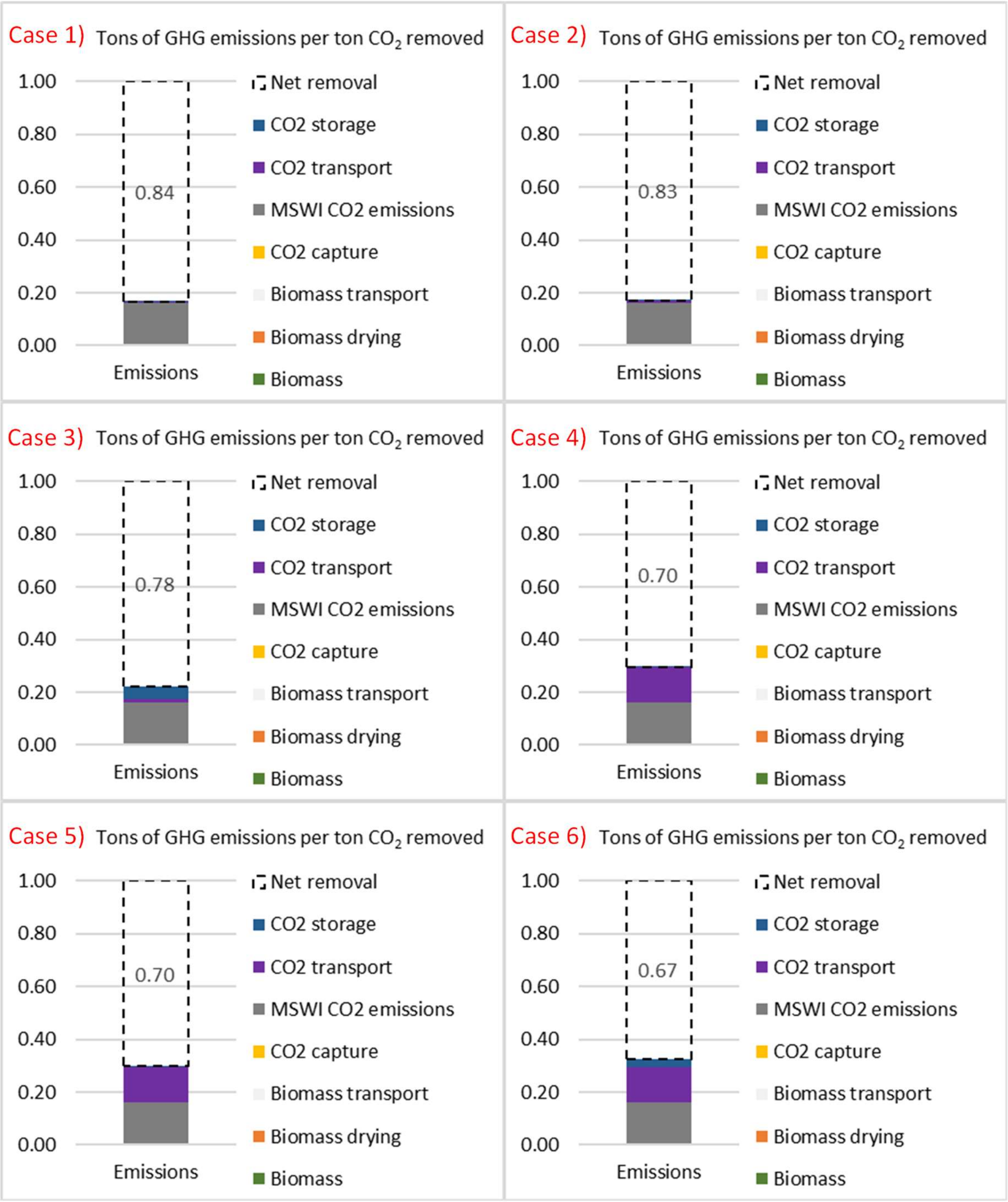


Figure 4.6: LCA results (climate impacts: tons of GHG emissions per ton of CO_2 permanently removed from the atmosphere) for different MSWI with CCS configurations, as generated with the LCA tool and specified in Table 4.8. Numbers in the dashed bar segments on top of the emissions indicate net CO_2 removal rates. MSWI operation in Switzerland in all cases; CO_2 storage in Switzerland (cases 1-3) and Iceland (cases 4-6). "Biomass" refers to the biogenic waste fraction. Only the fossil fraction of CO_2 emissions not captured at the MSWI plant generates climate impacts. Residual fossil CO_2 (not captured by the CO_2 capture unit) and downstream emissions are entirely assigned to CO_2 removal.

Table 4.9 shows an overview of key outcomes of the analysis of the six MSWI plant configurations with CCS, as specified in Table 4.8. While the plants generating electricity only (cases 3 and 6) show an electricity output almost twice as high as that of the CHP configurations, these can supply considerable amounts of low-temperature heat for district heating applications and their overall life-cycle energy efficiency is high: 85% vs. 16% for the "electricity only" configurations. The CO_2 removal factors mostly depend on the specification of biomass supply chains and characteristic, not the MSWI plant configurations as such.

Table 4.9: Key outcomes of the analysis of MSWI plants with CCS – six cases as specified in Table 4.8.

Key outcomes		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Removal	Removal efficiency	84%	83%	78%	70%	70%	67%
	Net CO_2 removed (t CO_2eq)	0.84	0.83	0.78	0.70	0.70	0.67
Avoidance	Net fossil-CO_2 captured (t CO_2eq)	0.92	0.92	0.92	0.92	0.92	0.92
Energy output	Electricity (MWh)	0.66	0.66	1.04	0.66	0.66	1.04
	Electricity / t biomass (MWh/dry t)	0.65	0.65	1.03	0.65	0.65	1.03
	Heat (GJ)	17.3	17.3	0.0	17.3	17.3	0.0
Biomass	Biomass utilized (wet t)	1.78	1.78	1.78	1.78	1.78	1.78
	CO_2 capture rate from biomass	85%	85%	85%	85%	85%	85%
	Energy efficiency from biomass	85%	85%	16%	85%	85%	16%

Figure 4.7 shows exemplary results for six different MSWI configurations for MSWI operation in Switzerland, as specified in Table 4.8 – with the exception that residual fossil CO_2 (not captured by the CO_2 capture unit) and downstream GHG emissions (i.e., those associated with CO_2 transport and storage) are assigned to CO_2 removal according to the biogenic carbon fraction of the waste (52%). The effect of this, compared to the default setting shown in Figure 4.6, is an increase in carbon removal efficiencies throughout all six cases by up to 16%-points for which the downstream emissions are the highest. Energy production related performance measures are not affected. With such a setting, carbon removal efficiencies of wood ad waste combustion with CCS are similar.

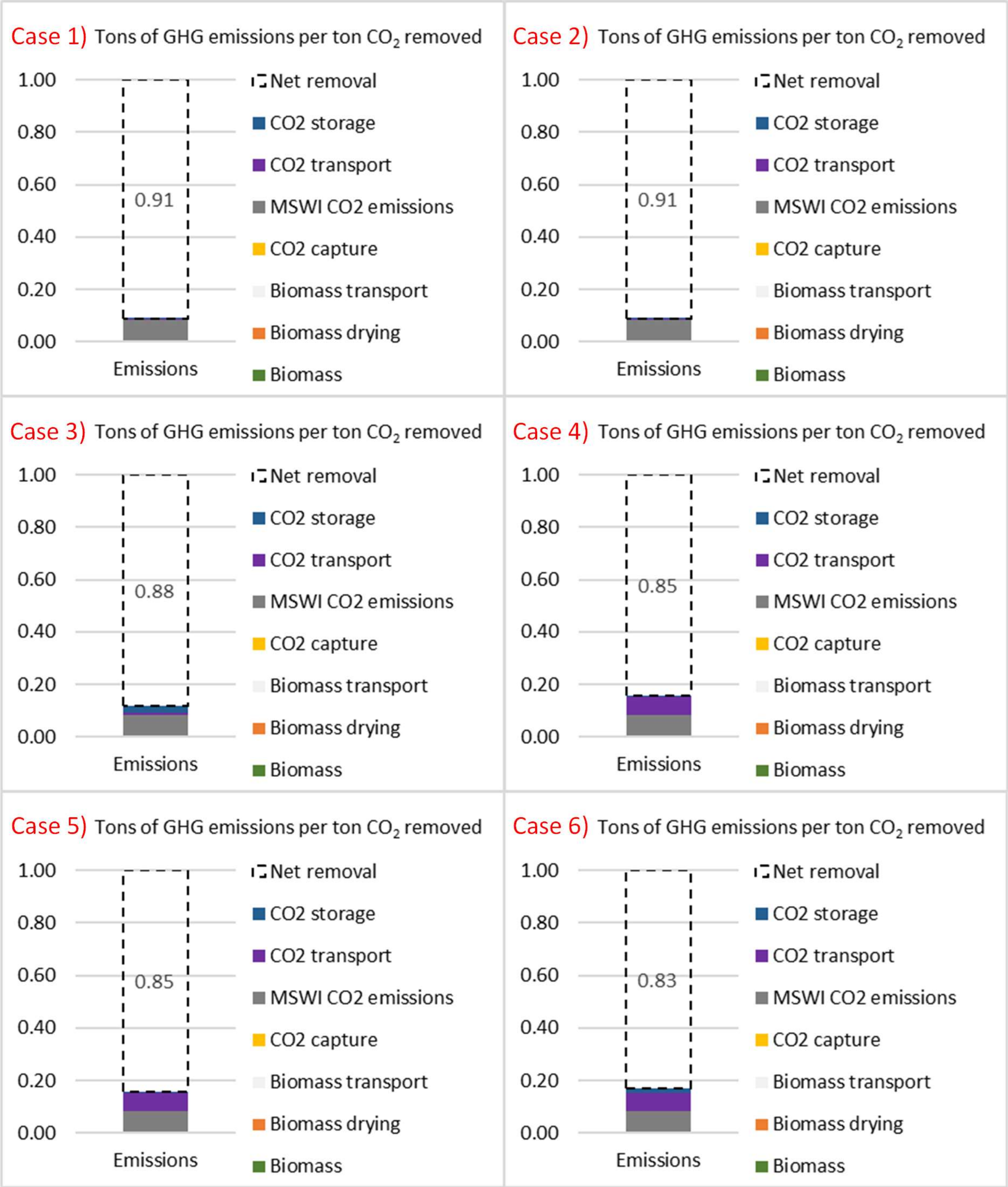


Figure 4.7: LCA results (climate impacts: tons of GHG emissions per ton of CO_2 permanently removed from the atmosphere) for different MSWI with CCS configurations, as generated with the LCA tool and specified in Table 4.8. Numbers in the dashed bar segments on top of the emissions indicate net CO_2 removal rates. MSWI operation in Switzerland in all cases; CO_2 storage in Switzerland (cases 1-3) and Iceland (cases 4-6). "Biomass" refers to the biogenic waste fraction. Only the fossil fraction of CO_2 emissions not captured at the MSWI plant generates climate impacts. Residual fossil CO_2 (not captured by the CO_2 capture unit) and downstream emissions are assigned to CO_2 removal according to the biogenic carbon fraction of the waste (52%).

4.4 (Coastal) Enhanced Weathering ((C)EW)

Enhanced weathering (EW) is a carbon dioxide removal method whereby crushed silicate minerals are spread on land ("coastal enhanced weathering", CEW, if spreading happens in coastal zones) to be naturally weathered by rainfall (waves and tidal currents in addition in coastal zones), releasing alkalinity and removing atmospheric CO_2 (Foteinis, Campbell and Renforth, 2023). Coastal EW can be considered as more promising than terrestrial EW, as large amounts of alkalinity released on land at scale could have adverse effects, especially since freshwater ecosystems are sensitive to changes in the pH levels and might be already affected by salinity and alkalinity due to anthropogenic activities and accelerated weathering. This limitation is less constraining in CEW, since the oceans are affected by acidification, seawater's average pH is much higher, and marine carbonate chemistry is less sensitive to alkalinity addition at a global scale (Foteinis, Campbell and Renforth, 2023).

CEW cannot be implemented in Switzerland but might still be of interest for compensating Swiss residual GHG emissions abroad as it is unlikely that all GHG removal required for reaching the Swiss net zero goal will take place in Switzerland (Der Bundesrat, 2022). Moreover, the fundamental principles of the enhanced weathering process as well as the main processes to be considered in an LCA do not depend on whether they take place in coastal areas, or on land far from the ocean. However, side effects (positive and negative) beyond carbon removal will be very different and depend on the type of land the rock material is applied to. As the quantification of those side effects is beyond the scope of this analysis, we consider LCA outcomes of the enhanced weathering LCA model we implemented in the LCA tool in terms of CDR service, which is based on an LCA of CEW as representative for terrestrial enhanced weathering. Swiss specific conditions in terms of geology and characteristic of domestically available rocks can be mimicked by adjusting the parameter representing the amount of CO_2 removed by EW per unit of crushed rock material spread, based on the analysis performed by (Ladner *et al.*, 2023). While (Foteinis, Campbell and Renforth, 2023) use a factor of 0.8 t CO_2 removed per ton of olivine, (Ladner *et al.*, 2023) consider an amount of 0.2-0.5 t CO_2 removed per ton of rock material as representative for Swiss conditions. From an international perspective this range seems to be at the lower end of specific CO_2 removal factors, which is specified as 0.2-1.1 t CO_2 removed per ton of rock material according to (Zhang *et al.*, 2023).

We implement a simple representation of (coastal) enhanced weathering in our LCA tool, based on (Foteinis, Campbell and Renforth, 2023). Recent research has shown substantial regional differences in terms of CO_2 sequestration per unit of rock spread, determined mostly by rock characteristics, (water) temperatures and grain sizes of the rock material spread (Ladner *et al.*, 2023; Zhang *et al.*, 2023; Ramasamy, Amann and Moosdorf, 2024). Due to lack of alternatives in terms of inventory data, we use olivine as our default rock material representing generic silicate material and the associated mining and crushing processes.

The EW process chain basically consists of four steps: Olivine or other rock mining, rock crushing (comminution), transport of crushed rock, and its (coastal) spreading. Parameters to be adjusted in the tool are the following:

- Country of rock mining, crushing and spreading: Switzerland, Norway, Iceland, and Greece
- Electricity source for olivine mining and crushing: country-specific grid mix, coal and natural gas power, geothermal (only in Iceland) and wind power
- Means of transport and transport distance for rock material (in total between mining and spreading of the crushed rocks): lorry, freight train, freight ship
- Specific CO_2 uptake of rock material: 0.2-0.5 t CO_2 removed per ton of rock for Swiss specific conditions and 0.8 t CO_2 removed per ton of rock representing a global representative value

Figure 4.8 shows exemplary results for six different CEW configurations, as specified in Table 4.10. Here, we assume that olivine mining, crushing, and (coastal) spreading will take place in the same country. Due to a lack of reliable information, location-specific aspects of CO_2 uptake like the impact of climate conditions are not considered.

Table 4.10: Specification of cases for quantifying GHG emissions of (C)EW.

case	**Country of olivine mining, crushing and spreading**	**Olivine transport (overall)**	**Power source for olivine mining and crushing**	**Specific CO_2 uptake [t CO_2/t of rock]**
1	Switzerland	Lorry: 300km Freight train: 100km	country-specific grid mix	0.2
2	Switzerland	Lorry: 50km	country-specific grid mix	0.2
3	Switzerland	Lorry: 300km Freight train: 100km	country-specific grid mix	0.5
4	Greece	Lorry: 500km Ship: 1000km Freight train: 200km	country-specific grid mix	0.8
5	Greece	Lorry: 500km Ship: 1000km Freight train: 200km	coal	0.2
6	Iceland	Lorry: 50km	geothermal	0.8

The results show that on the one hand very high carbon removal rates seem to be possible, close to 100% (case 6); but that on the other hand unfavorable conditions can reduce the net removal rate substantially, down to about 40% in our case 5. Most important factors are a) rock transport means and distance, with lorries causing the highest GHG emissions by far (case 1 vs. case 2), and b) the specific CO_2 removal factor of the rock material spread. Comparing cases 1 and 3 shows that for EW in Switzerland, all other factors kept constant, a CO_2 removal factor of 0.2 results in a net removal rate of 0.65, while a CO_2 removal factor of 0.5 results in a net removal rate of 0.86 – higher factors reduce the required amount of rock mining, crushing and transport. Since the amount of electricity for olivine mining and crushing is comparatively small, even the use of fossil energy carriers for power supply of these processes does not cause GHG emissions which change the overall climate impacts in a noticeable way (case 5).

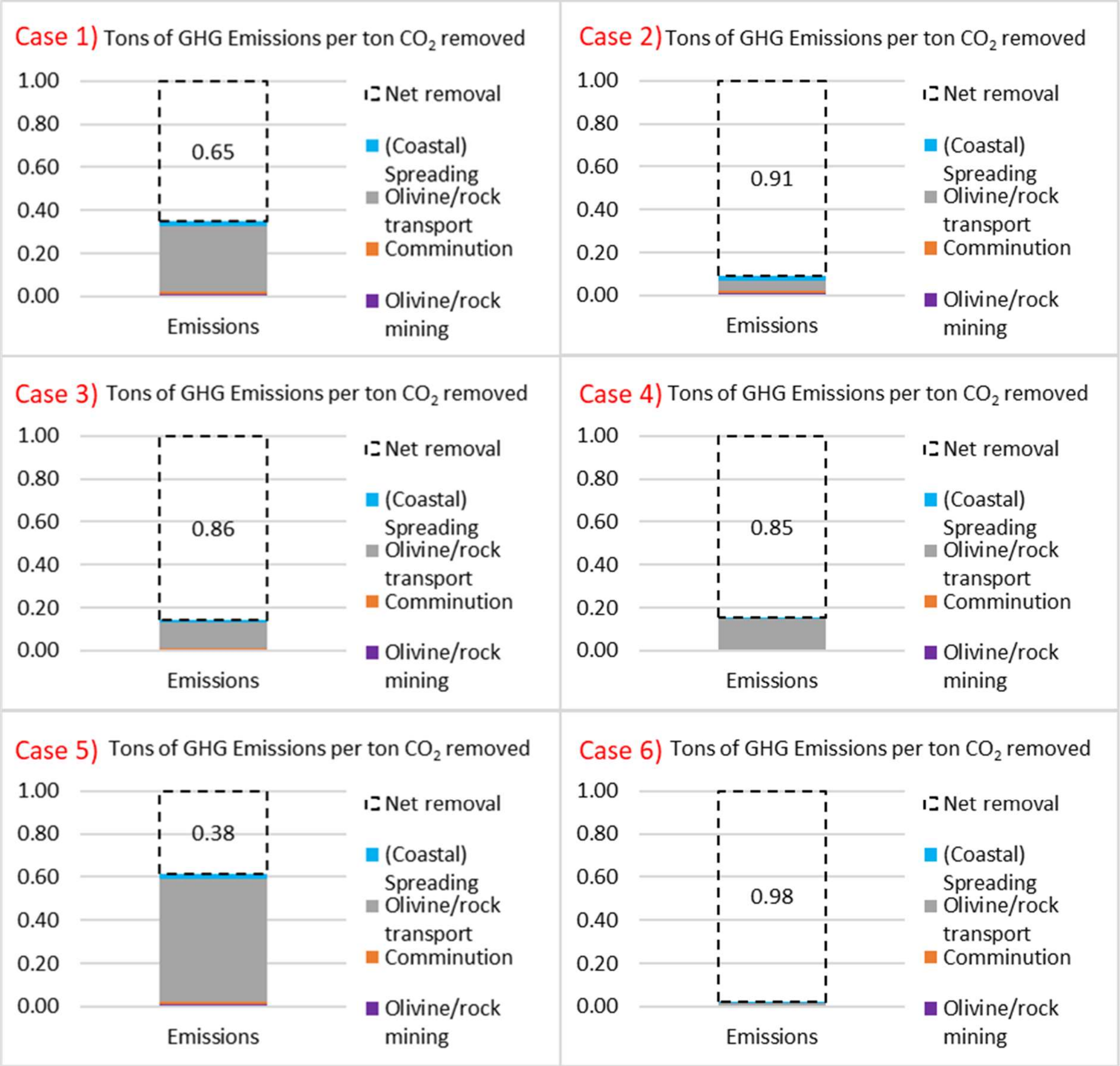


Figure 4.8: LCA results (climate impacts: tons of GHG emissions per ton of CO_2 permanently removed from the atmosphere) for different (C)EW configurations, as generated with the LCA tool and specified in Table 5.7. Numbers in the dashed bar segments on top of the emissions indicate net CO_2 removal rates. Application in Switzerland (cases 1-3), Greece (cases 4, 5), and Iceland (case 6).

4.5 Ocean liming (OL)

Ocean liming (OL) is a CDR method whereby particulate calcium oxide or hydroxide is spread to surface ocean waters to take up and fix atmospheric CO_2. Ocean liming cannot be implemented in Switzerland but might still be of interest for compensating Swiss residual GHG emissions abroad as it is unlikely that all GHG removal required for reaching the Swiss net zero goal will take place in Switzerland (Der Bundesrat, 2022).

The removal of 1 ton of CO_2 from the atmosphere can be achieved through the spreading and the dissolution of 1 ton of CaO (“quicklime”) in surface ocean waters. To produce 1 ton of CaO, 1.786 tons of crushed limestone/calcite needs to be calcined (which requires substantial amount of heat and electricity), with the remaining 0.786 t being CO_2 emissions. Thereafter, CaO can be directly spread to the ocean, where it will be hydrated. Finally, the hydrated CaO in the ocean will react with and uptake atmospheric CO_2 to mainly form stable and inert bicarbonate ions and calcium (Foteinis *et al.*, 2022).

We implement a simple representation of OL in our LCA tool, based on (Foteinis *et al.*, 2022). It basically consists of six steps: Limestone mining, its crushing and washing, quicklime production, its hydration, lime transport, and ocean spreading. An important assumption is that the emissions generated from limestone decomposition are captured and stored (applying CCS), whereas the emissions from fuel combustion for high-temperature heat supply are emitted to the atmosphere. Parameters to be adjusted are the following:

- Location of mining and processing: Greece, Norway, Iceland
- Location of ocean spreading
- Electricity and heat sources for limestone mining and processing and lime production
- Electricity source for ocean spreading
- Transport means and distances, overall for mined material and for quicklime
- Travelled distance of ocean spreading ship

Due to missing reliable information, we refrain from quantifying any effect of the environmental conditions in which lime is spread, e.g., ocean temperature. The outcomes presented here represent hypothetical current practices, as no large-scale implementation in practice yet exists. In the future, energy requirements along the process chain are likely to be reduced, as substantial energy saving potential seems to exist (De Marco *et al.*, 2024).

Figure 4.9 shows exemplary results for six different OL configurations, as specified in Table 4.11. Here, we assume that mining, processing, and quicklime production take place in the same country, where also the ship performing the ocean spreading takes off.

Table 4.11: Specification of cases for quantifying GHG emissions and net CO_2 removal rates of OL.

case	**Location of limestone mining, processing and quicklime production**	**Limestone and quicklime transport: means and distances**	**Limestone and quicklime production: electricity source**	**Limestone and quicklime production: heat source**	**Ocean spreading: electricity source**	**Ocean spreading: shipping distance**
1	Iceland	Lorry: 50km Ship: 200km Freight train: 200km	country-specific grid mix	natural gas	country-specific grid mix	2000km
2	Iceland	Lorry: 10km Ship: 100km Freight train: 100km	geothermal	wood chips	geothermal	10000km
3	Norway	Lorry: 100km Ship: 500km Freight train: 500km	country-specific grid mix	wood chips	country-specific grid mix	2000km
4	Norway	Lorry: 1000km Ship: 200km Freight train: 200km	natural gas turbine	natural gas	natural gas turbine	10000km
5	Greece	Lorry: 200km Ship: 1000km Freight train: 200km	country-specific grid mix	wood chips	country-specific grid mix	2000km
6	Greece	Lorry: 1000km Ship: 1000km Freight train: 200km	wind power	natural gas	wind power	10000km

The results show that high carbon removal efficiencies (up to 90%) are possible, but only if the energy for the quicklime production is provided with very low GHG emissions and transport distances for limestone and quicklime – especially by truck – are low (cases 2 and 3). In general, GHG emissions from limestone mining, crushing and washing, and ocean spreading are comparatively minor. Quicklime production using fossil energy sources and material transport by truck over long distances reduces the net removal rate substantially, down to around 0.3 (cases 4 and 6).

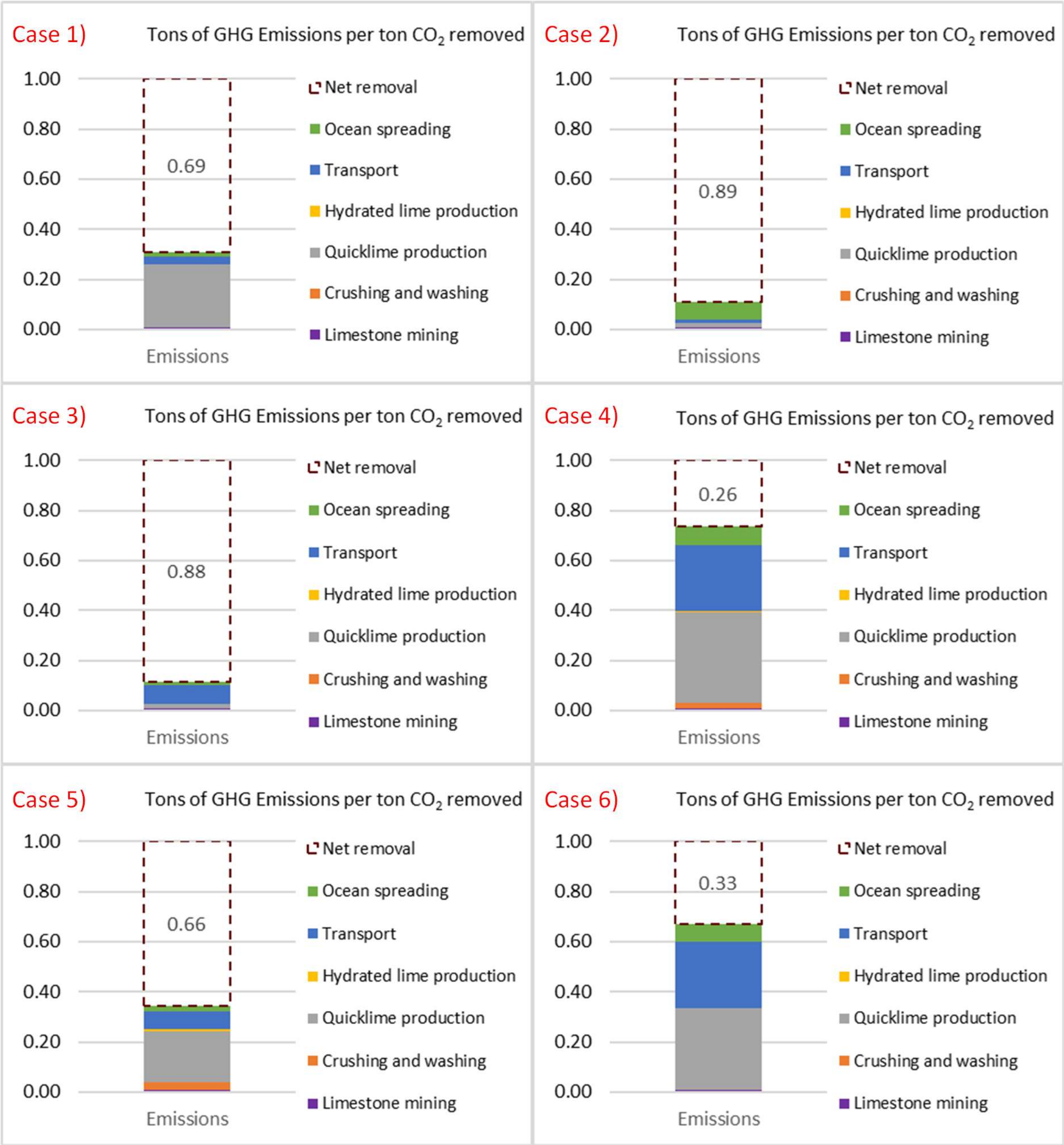


Figure 4.9: LCA results (climate impacts: tons of GHG emissions per ton of CO_2 permanently removed from the atmosphere) for different OL configurations, as generated with the LCA tool and specified in Table 4.11. Numbers in the dashed bar segments on top of the emissions indicate net CO_2 removal rates. Application in Iceland (cases 1, 2), Norway (cases 3, 4), and Greece (cases 5, 6).

4.6 Comparing different CDR methods regarding their climate impacts and CO_2 removals

Comparing different CDR methods regarding their effectiveness in terms of CO_2 removal in a meaningful way is not straightforward, since to some extent it is comparing apples and pears when it comes to methods with the sole purpose of removing CO_2 from the atmosphere on the one hand (e.g., DACCS) and other CDR methods with CO_2 removal rather as a co-benefit (e.g., MSWI with CCS) on the other hand. Uncertainties regarding the permanence of CO_2 removal, presence of potential co-benefits and trade-offs, location specificities which cannot be represented by our generic LCA models as well as the status of development and implementation of CDR methods in real life are other differences, which must be considered in such comparisons.

Nevertheless, we perform such a comparison based on our functional unit of "one gross ton of CO_2 permanently removed from the atmosphere" and quantify associated life cycle GHG emissions and thus the net GHG removal rates for the different CDR methods which are included in our LCA tool. For each of the CDR methods we include four options, which are supposed to represent "realistic" parameter settings, seem to be of interest from a Swiss perspective, and also show the variabilities of GHG removal efficiencies considering the given parameter space to some extent. In addition to the GHG removal efficiencies, we provide the amounts of biomass use and the amounts of by-products (i.e., heat and/or electricity) generated for BECCS and biochar-to-soil applications as well as energy use for DACCS.

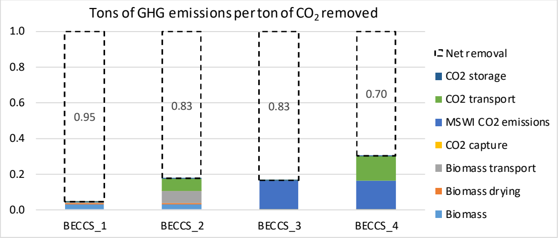
Figure 4.10 shows LCA results (climate impacts: tons of GHG emissions per ton of CO_2 permanently removed from the atmosphere) and net carbon removal rates for all five CDR methods addressed here in comparison, as specified in Table 4.12.

Table 4.12: Specification of CDR configurations for visualization of GHG emissions and net CO_2 removal rates shown in Figure 4.10. MSW: Municipal Solid Waste. CO_2 storage depth for BECCS and DACCS: 3000m. For MSW incineration: all GHG emissions are allocated to the biogenic CO_2 stored, i.e., to the CDR service. CO_2 capture rates: 90% for wood combustion, 85% for MSW incineration. Biochar application rate: 1 t/ha. No fertilizer demand reduction due to biochar application considered. LT: Low Temperature; HT: High Temperature.

BECCS	BECCS_1	BECCS_2	BECCS_3	BECCS_4
biomass type	spruce	beech	MSW	MSW
biogenic carbon fraction	100%	100%	52%	52%
location of power/MSWI plant	CH			
plant configuration	electricity only	electricity only	CHP	CHP
location of CO2 storage	CH	Iceland	CH	Iceland
energy source for biomass drying and CO2 capture	bio-energy plant internal			
electricity for CO2 injection and storage	grid			
biomass moisture after road-side drying	40%	40%	n.a.	n.a.
biomass transport	lorry: 50km	lorry: 200km train: 300km	n.a.	n.a.
CO2 transport distance (pipeline)	4000km	50km	4000km	50km
Biochar-to-soil	Biochar_1	Biochar_2	Biochar_3	Biochar_4
biomass type	spruce	spruce	beech	beech
biomass transport	lorry: 50km	lorry: 300km train: 1000km ship: 1000km	lorry: 100km train: 200km	lorry: 100km train: 200km
biomass drying: before/after transport	after	after	after	before
biomass moisture after road-side drying	40%			
pyrolysis temperature (°C)	600	600	400	400
energy for biomass drying	internal from by-products			natural gas
energy for pyrolysis	internal from by-products			
location: pyrolysis and biochar application	CH			
biochar transport	lorry: 50km tractor: 10km	lorry: 50km tractor: 10km	lorry: 100km tractor: 30km	lorry: 100km tractor: 30km
DACCS	DACCS_1	DACCS_2	DACCS_3	DACCS_4
DAC type	LT solid sorbent			HT solvent
DAC location	CH	CH	Iceland	CH
DAC electricity supply	grid	grid	geothermal	grid
DAC heat supply	waste heat	waste heat	waste heat	natural gas
CO2 storage location	CH	Iceland	Iceland	Iceland
CO2 transport distance (via pipeline)	10km	4000km	10km	4000km
Coastal enhanced weathering	EW_1	EW_2	EW_3	EW_4
location: olivine mining, crushing, spreading	CH	CH	CH	Norway
electricity source for mining and crushing	grid	grid	natural gas	grid
olivine transport	Lorry: 50km	Lorry: 50km	Lorry: 200km Train: 200km	Lorry: 200km Train: 1000km
specific CO2 uptake of rock material $[t_{CO2}/t_{rock}]$	0.2	0.5	0.2	0.8
Ocean liming	OL_1	OL_2	OL_3	OL_4
location: limestone mining and processing	Iceland	Iceland	Norway	Norway
electricity source for mining and processing	grid	geothermal	grid	natural gas
heat source for mining and processing	natural gas	wood chips	wood chips	natural gas
overall transport: limestone and quicklime	lorry: 50km ship: 200km train: 200km	lorry: 10km ship: 100km train: 100km	lorry: 100km train: 500km ship: 500km	lorry: 1000km ship: 200km train: 200km
ocean spreadig: electricity source	grid	grid	grid	natural gas
ocean spreading: shipping distance	2000km	10000km	2000km	10000km

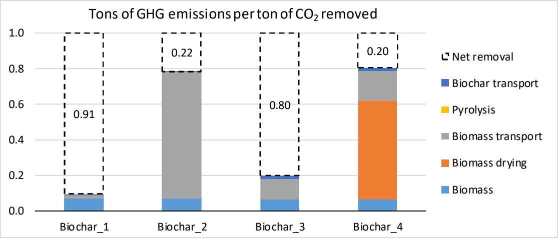
Bio-energy carbon capture and storage

	BECCS_1	BECCS_2	BECCS_3	BECCS_4
Biomass	0.0297	0.0297	0.0000	0.0000
Biomass drying	0.0045	0.0045	0.0000	0.0000
Biomass transport	0.0096	0.0682	0.0000	0.0000
CO2 capture	0.0000	0.0000	0.0005	0.0005
MSWI CO2 emissions	0.0000	0.0000	0.1629	0.1629
CO2 transport	0.0002	0.0690	0.0005	0.1327
CO2 storage	0.0011	0.0018	0.0022	0.0034
Net removal	**0.95**	**0.83**	**0.83**	**0.70**



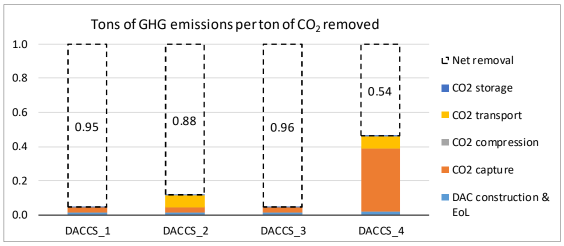
Biochar

	Biochar_1	Biochar_2	Biochar_3	Biochar_4
Biomass	0.0713	0.0713	0.0669	0.0669
Biomass drying	0.0000	0.0000	0.0000	0.5506
Biomass transport	0.0153	0.7055	0.1114	0.1671
Pyrolysis	0.0024	0.0024	0.0029	0.0029
Biochar transport	0.0050	0.0050	0.0160	0.0160
Net removal	**0.91**	**0.22**	**0.80**	**0.20**



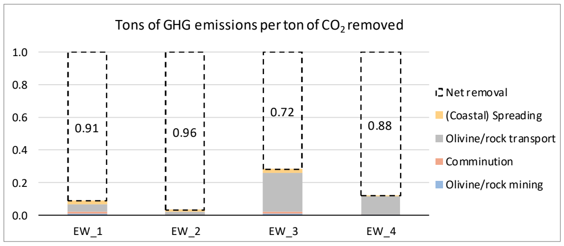
Direct air carbon capture and storage (DACCS)

	DACCS_1	DACCS_2	DACCS_3	DACCS_4
DAC construction & EoL	0.0141	0.0141	0.0141	0.0209
CO2 capture	0.0306	0.0306	0.0286	0.3696
CO2 compression	0.0000	0.0000	0.0000	0.0000
CO2 transport	0.0000	0.0690	0.0000	0.0690
CO2 storage	0.0011	0.0018	0.0018	0.0018
Net removal	**0.95**	**0.88**	**0.96**	**0.54**



(Coastal) Enhanced Weathering ((C)EW)

	EW_1	EW_2	EW_3	EW_4
Olivine/rock mining	0.0128	0.0051	0.0128	0.0032
Comminution	0.0094	0.0037	0.0096	0.0023
Olivine/rock transport	0.0468	0.0187	0.2387	0.1113
(Coastal) Spreading	0.0229	0.0092	0.0229	0.0057
Net removal	**0.91**	**0.96**	**0.72**	**0.88**



Ocean liming (OL)

	OL_1	OL_2	OL_3	OL_4
Limestone mining	0.0074	0.0074	0.0074	0.0074
Crushing and washing	0.0023	0.0011	0.0013	0.0208
Quicklime production	0.2492	0.0180	0.0190	0.3631
Hydrated lime production	0.0004	0.0002	0.0002	0.0037
Transport	0.0310	0.0118	0.0709	0.2669
Ocean spreading	0.0168	0.0702	0.0165	0.0747
Net removal	**0.69**	**0.89**	**0.88**	**0.26**

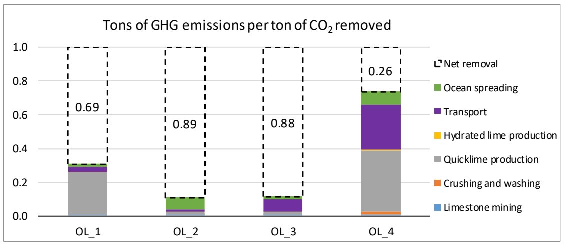


Figure 4.10: Comparison of life cycle GHG emissions and net CO_2 removal rates of different CDR methods with four specific parameter settings each, as specified in Table 4.12. Stacked colored bars show life cycle GHG emissions; numbers in the dashed bar segments on top of the emissions indicate net CO_2 removal rates. "By-products" of CDR, e.g., heat and electricity generation in case of BECCS and biochar application, are not shown here, but provided in Table 4.13.

Carbon net removal efficiencies of BECCS systems are in a range of 70-95%. These percentages represent "best" and "worst case" conditions (from a kind of realistic Swiss perspective), respectively, with CO_2 storage in Switzerland or Iceland. The best-case configuration uses locally harvested wood with geological CO_2 storage in the proximity of the wood power plant avoiding long transport distances. The worst-case configuration uses municipal solid waste in an incineration plant with a rather low CO_2 capture rate and CO_2 has to be transported to the geological storage in Iceland, with residual fossil CO_2 (not captured by the CO_2 capture unit) and downstream GHG emissions (i.e., those associated with CO_2 transport and storage) entirely assigned to CO_2 removal.[52] Further reduction of the carbon removal efficiency would be possible, but only in a – from the current Swiss perspective – probably unrealistic setting, which needs to be avoided: using wood from non-sustainable forestry or dedicated plantations, which would come along with land-use related GHG emissions; long-distance biomass transport, especially by truck; biomass drying using fossil fuels; and storage of CO_2 far beyond Iceland.

The selected biochar cases for use of biochar as soil amendment in Switzerland exhibit net carbon removal rates in a range of around 20-90%. The two cases with low CO_2 removal rates around 20% include long-distance wood transport and/or the use of fossil energy for wood drying – both should be avoided to effectively remove carbon from the atmosphere. Since per unit of CO_2 gross removal more wood is needed compared to wood combustion with CCS (as a large carbon fraction ends up in syngas and bio-oil), minimizing biomass transport to minimize indirect GHG emissions is even more important for biochar compared to direct wood combustion. Thus, small scale pyrolysis plants using locally available biomass seem to be the preferred option. Here we have assumed that the energy for both biomass drying and pyrolysis operation is provided by burning the pyrolysis by-products – which represents the most realistic option from our perspective. Using fossil energy carriers for these processes would increase the indirect GHG emissions substantially.

DACCS systems show very high net carbon removal efficiencies (here between 88% and 96%) if energy from renewable (or waste) sources is used for the CO_2 capture process (cases 1-3). This is easier for low-temperature DAC processes, as the high-temperature process modeled here (case 4) needs heat from a combustion process and proper renewable sources are limited to wood, biomethane and hydrogen – which are all either limited in terms of availability or currently not available. Alternatively, also the emissions from heat supply can be fed into the DAC unit to avoid the associated CO_2 emissions – such an implementation with natural gas combustion as heat source would, however, increase the CO_2 storage volume needed by about 30% (Qiu *et al.*, 2022). Here, with natural gas used for heat supply and not capturing associated CO_2 emissions for the high-temperature DAC process in case 4, the net carbon removal efficiency amounts to only 54%. Storing the CO_2 in the proximity of the DAC units is beneficial from a net carbon removal efficiency perspective, but also CO_2 transport per pipeline from Switzerland to Iceland (case 2) does not lead to major GHG emissions.

Enhanced weathering consistently shows high net carbon removal efficiencies – here in a range of 72-96%. The only factor with an important impact on results generating potentially substantial amounts of GHG emissions is the transport of rock material, especially truck transport. If these transport activities can be limited to maximum a few hundred kilometers, efficient carbon removal seems to be possible. In general, characteristics of rock materials available domestically in Switzerland does not seem to be favorable, as their specific CO_2 uptake is at the lower end of the global range. Even more important are low transport distances. However, the fact that there is hardly any real evidence on this CDR method needs to be kept in mind.

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[52] Assigning residual fossil CO_2 (not captured by the CO_2 capture unit) and downstream emissions to the CDR service according to the biogenic carbon fraction in the waste results in an increase of net carbon removal efficiencies of up to about 15%, see Figure 4.6 in comparison to Figure 4.7.

Ocean liming represents the least developed and most hypothetical CDR method included in this comparison and is thus associated with high uncertainties. Its net carbon removal efficiency (here in between 26% and 89%) depends mainly on the heat source used for quicklime production and overall transport activities along the process chain. Using heat from renewables is key for efficient carbon removal and also rather short transport distances are important.

The most important common learnings from this comparison are that 1) resources needed – be it biomass or minerals/rocks – should be sourced locally to minimize transport processes, and that 2) low-carbon energy supply for all CDR methods is important to allow for high carbon removal efficiencies.

For DACCS, BECCS and biochar-to-soil applications, we provide further outputs of the LCA in terms of biomass and energy related performance indicators. These can be important from the perspective of the energy system in which the CDR methods are operated and from the biomass utilization perspective. For DACCS, we provide electricity and heat demand for CO_2 capture, which depends on the ambient climate (temperature and humidity)[53]. For BECCS, we provide net energy efficiency[54] of the wood and MSW incineration plants, the amount of (wet) biomass needed and the net electricity and heat output per one ton of gross CO_2 removal, and the amount of electricity generated per ton of (dry) biomass input. For biochar-to-soil applications we provide the CO_2 removal rate from biomass (i.e., the fraction of carbon in the biomass, which is permanently removed from the atmosphere, assuming combustion of syngas and bio-oil from pyrolysis), the wet biomass use per ton of gross CO_2 removal, the net electricity and heat output (converting available syngas and bio-oil from pyrolysis), and the amount of electricity generated per ton of (dry) biomass input. All these parameters are provided in Table 4.13.

BECCS and biochar-to-soil applications represent so called "multi-output processes", as they provide not only the CO_2 removal service (or "negative CO_2 emissions") as products, but also energy as one of their outputs. In LCA, such multi-output processes can be dealt with in different ways: either quantifying the overall environmental burdens for the "basket of products" the multi-output process generates and comparing them to those of a "reference system" providing the same basket of products, or – if product-specific environmental burdens are of interest – applying allocation or system expansion (with substitution). Allocation corresponds to the subdivision of the overall environmental burdens according to for example market prices or energy contents of the individual products of the multi-output process; system expansion (with substitution) corresponds to considering "emission credits" representing potentially avoided production due to substitution of alternative (default) production pathways of by-products of a multi-output process. Here, we refrain from applying any of these concepts, as the choice of reference systems as well as substituted products is arbitrary without a specific context of CDR implementation and would depend on, for example, location and time and the energy system in which the CDR methods are applied.

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[53] This should be the case for both low- and high-temperature processes. However, we only have solid data on this aspect for our low-temperature solid sorbent system and therefore must refrain from implementing this climate dependency for the high-temperature process.

[54] I.e., energy in terms of electricity and heat output as fraction of the energy content of the biomass input.

Table 4.13: Energy related key performance parameters of BECCS, DACCS and biochar-to-soil application.

BECCS	BECCS_1	BECCS_2	BECCS_3	BECCS_4
	Wood power plant with CCS	Wood power plant with CCS	MSWI with CCS, CHP configuration	MSWI with CCS, CHP configuration
Power/CHP plant location	Switzerland			
CO_2 capture rate [%]	90	90	85	85
net energy efficiency [%]	15	15	85	85
biomass utilized per ton of gross CO_2 removal [t(wet)/t(CO_2)]	3.08	3.12	1.78	1.78
net electricity output per ton of dry biomass [MWh/t(dry)]	0.79	0.75	0.65	0.65
net heat output per ton of gross CO_2 removal [GJ/t(CO_2)]	0	0	17.3	17.3
net electricity output per ton of gross CO_2 removal [MWh/t(CO_2)]	0.48	0.47	0.66	0.66
Biochar-to-soil	Biochar_1	Biochar_2	Biochar_3	Biochar_4
Biochar production and application	Switzerland			
Tree species used	spruce	spruce	beech	beech
Heat source for biomass drying(internal/external)	internal			external
CO_2 removal rate (% of carbon in biomass permanently removed) [%]	38	38	32	32
biomass utilized per ton of gross CO_2 removal [t(wet)/t(CO_2)]	7.4	7.4	8.9	8.9
net heat output per ton of gross CO_2 removal [GJ/t(CO_2)]	2.8	2.8	2.6	9.9
net electricity output per ton of gross CO_2 removal [MWh/t(CO_2)]	0.91	0.91	1.02	1.11
net electricity output per ton of dry biomass [MWh/t(dry)]	0.46	0.46	0.51	0.56
DACCS	DACCS_1	DACCS_2	DACCS_3	DACCS_4
DAC type	LT sorbent	LT sorbent	LT sorbent	HT solvent
DAC operation	CH	CH	IS	CH
electricity consumption per ton of gross CO_2 removal [GJ/t(CO_2)]	0.31	0.31	0.25	1.2
heat consumption per ton of gross CO_2 removal [GJ/t(CO_2)]	4.2	4.2	3.2	6.3

Some general and qualitative conclusions regarding the preferred way to use biomass are still possible without a complete system perspective and the limited scope of our analysis. As sustainable biomass from Swiss forests represents a limited resource, it should be used in line with overarching goals. If the goal is maximizing electricity production, large-scale biomass power plants are probably the best option as they will exhibit the highest electric efficiencies. Increasing plant capacities will, however, also lead to an increase in wood transport distances. If the goal would be maximizing the contribution of woody biomass to CDR, such wood power plants equipped with CCS seem to be the most meaningful option, as the CO_2 capture rate at the power plant corresponds to the gross CO_2 removal rate (i.e., the fraction of carbon in the biomass, which is permanently removed from the atmosphere) and CO_2 capture rates of 90% or more for such power plants are state-of-the-art today. From a carbon removal perspective and compared to such wood power plants with CCS, biochar production with slow pyrolysis and subsequent application to Swiss agricultural land seems to be less preferable as, according to our calculations, only 30-40% of the carbon in the biomass feedstock will be "permanently"[55] removed from the atmosphere – the rest ends up in the by-products of the pyrolysis process, which are usually burned with a release of carbon as CO_2, or will not permanently remain in the soil but will be re-emitted as CO_2, as biochar is not entirely stable. Electricity generation from wood combustion with CCS also seems to be preferable in terms of energy production in comparison to biochar-to-soil applications: Net electricity outputs are almost twice as high for wood power plants with CCS compared to biochar systems ("net electricity output per ton of dry biomass" in Table 4.13). In practice, the answer to the question for which purpose biomass should be used, will also be determined by factors beyond those considered in our analysis.

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[55] In our biochar LCA, we assumed a CO_2 removal period of 100 years as equivalent to permanent removal. Such a short time is, however, not equivalent with permanence in terms of climate impacts, as most recent research has shown (Brunner, Hausfather and Knutti, 2024). Their findings represent an additional argument supporting the use of biomass in BECCS systems as opposed to biochar-to-soil applications.

5 Recommendations for further research

Based on the status of our work and the scope of this project, we identify directions of further research beyond this work; or, in other words, knowledge gaps, which are obvious today, relevant in the Swiss context, and which the work in this project will not be able to close.

5.1 Interdisciplinary character

It is important to realize that CDR is a very interdisciplinary (research) topic and that collaboration between different research domains on the one hand, and between research, industry and society on the other hand will be required. Research domains to be mentioned include for example forestry and forest modelling, the agricultural sector, process engineering, the building sector, economic research, biodiversity assessment, energy system modelling, regulatory aspects and law, sociology, etc. Only such a combination and synergistic use of expertise will allow for a comprehensive characterization of CDR methods regarding their potentials, costs, environmental impacts, development perspectives, etc. – which should represent the basis for prioritization of investments and policies.

5.2 Specific gaps in LCA of CDR methods

Several CDR methods overarching issues, which deserve further attention and work, are highlighted in the following:

- Environmental burdens beyond impacts on climate change: Most of the CDR related LCA studies either address only impacts on climate change to quantify the net efficiency of CO_2 removal, or they provide additional indicators for impacts on ecosystems and human health in a very generic way on the midpoint level using one of the common LCIA methods. Alternatively, some studies quantify resource consumption in terms of for example land and water based on cumulative inventory results. None of this is very useful for evaluating the more comprehensive environmental performance of CDR in a decision-making context. Applying complementary approaches would be more useful, e.g., performing LCA and applying the planetary boundary concept, which allows to better determine the relevance of certain burdens caused. Also complete aggregation of environmental impacts could be performed, for example applying the ecological scarcity method (BAFU, 2021).
- Spatial resolution of LCA: As impacts on ecosystems, human health, and natural resources most often crucially depend on where these are caused, applying generic impact assessment methods with generic damage factors is unlikely to represent “real” impacts, or is at least associated with very high uncertainties. Performing regionalized LC(I)A represents the way forward in this context. This would also allow to comparatively assess a range of CDR methods beyond impacts on climate change based on local boundary conditions.
- Common denominator or functional unit: Comparative LCA requires a common functional unit, or in other words, a common denominator. In case of LCA of CDR methods, the most straightforward choice is “One unit of CO_2 permanently removed from the atmosphere”, often referred to as “gross amount of CO_2 removed” and as applied for the comparative evaluation in this analysis. However, this choice indicates that CDR is the main purpose of any process removing CO_2 from the atmosphere., which is in practice probably not always correct. Further, dealing with the multifunctionality of CDR methods, which provide other products and services beyond CDR, requires subjective choices by LCA analysts. Thus, LCA results for such CDR methods are often hard to directly compare.
- Permanence of CO_2 removal: Basically, all CDR methods which rely on natural processes for CO_2 removal, such as biochar-to-soil application, enhanced weathering, long-term storage of biogenic CO_2 I wooden construction materials, forest-related CDR, and marine CDR, are subject to considerable uncertainties regarding permanence of CO_2 removal.

Further, there is not even a commonly accepted definition of the term "permanence" in this context – for some CDR methods it makes a big difference, whether this is interpreted as a period of 30, 100, or thousands of years, as releases of captured CO_2 back into the atmosphere might not happen in a linear way.

Only very recently, (Brunner, Hausfather and Knutti, 2024) have demonstrated that "a CO_2 storage period of less than 1000 years is insufficient for neutralizing remaining fossil CO_2 emissions under net zero emissions." This new evidence needs to be considered in future LCA of CDR methods which do not rely on permanent geological CO_2 storage.

- Direct and indirect land use change related impacts on climate change: Climate impacts as a result of direct and indirect land use change – especially relevant for CDR methods involving biomass – are often quantified in a superficial way or even not at all. Reasons are that such impacts are highly location specific and that there is no commonly accepted procedure of how to quantify such impacts in the CLA community.
- Access to transparent and reliable information and data: CDR methods being developed today and potentially entering the market tomorrow are often subject to confidentiality concerns, mainly for business related reasons. Resulting limited access to transparent and reliable information and data represents an issue potentially undermining quality of LCA studies and thus trust in their outcomes.
- Uncertainty analysis: Formal methods for analyzing uncertainties such as global sensitivity analysis could be employed (Kim *et al.*, 2022).

5.2.1 Biochar

For biochar used as soil amendment, the main LCA related issue is the lack of reliability of generically performed LCA studies and their results – as case-specifics and local boundary conditions regarding for example biochar quality, soil type, and common agricultural practices play important roles regarding the effective CO_2 removal and other environmental impacts. In a Swiss context, large uncertainties remain (BAFU, 2023). Further, additional use cases for biochar beyond its use as soil amendment should be investigated by means of LCA. Such studies are currently largely missing.

5.2.2 BECCS

As there is a broad range of biomass use options (including and excluding CCS and CDR), evaluations of their environmental performance should include counterfactual scenarios considering case-specific boundary conditions. This is especially relevant for residual biomass, which represents a constrained resource, and dedicated biomass crops, which occupy often land which could be used for other purposes. Further, new technology options are being developed, which should be evaluated by means of LCA.

Importantly, future LCA studies of BECCS systems (especially those including biomass from forests) should not rely on the concept of "carbon neutrality"[56] of the biogenic carbon and CO_2 fluxes, i.e., should not be based on the assumption that the use of biomass would have negligible impacts on the development of carbon stocks in forests without considering management practices of forests to produce the biomass (Strengers *et al.*, 2024). I other words, ay LCA of BECCS systems should include potential impacts of biomass use on carbon stocks in forests. Despite of the fact that the assumption of "carbon neutrality" represents common practice in many LCA studies today (also this study), it cannot be assumed to represent real life in many cases. In real-life situations, producing biomass from forests

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[56] The term "carbon neutral" is used to refer to situations in which producing biomass from forests for wood products and bioenergy results in zero or negligible net emissions of CO_2 to the atmosphere, when the complete life cycle of forest growth (and re-growth) and harvesting and consumption of biomass is considered. This can occur if CO_2 emissions from harvesting and using forest biomass, including burning some for bioenergy, are exactly balanced by carbon sequestration in the forests that produced the biomass (Strengers *et al.*, 2024).

for use in wood products and for bioenergy (but also for biochar production) can result in decreasing, constant, or increasing levels of carbon stocks in forests and these effects should be included in any LCA of BECCS systems (Strengers *et al.*, 2024).

5.2.3 DACCS

The main challenge for DACCS related LCA is to keep track with the ongoing developments and new players with new CO_2 capture processes entering the market. LCA performed at early development stages can help to prioritize technology development.

5.2.4 Enhanced Weathering

From our point of view, verification of model-based quantification of effective and permanent CO_2 removal due to enhanced rock weathering represents a major challenge, which is very relevant for LCA. Lack of experience with this kind of CDR method and thus a lack of reliable data, applicable for LCA, also needs to be mentioned.

5.2.5 Long-term CCU

The current lack of a standardized and commonly accepted dynamic accounting framework for climate impacts associated with temporary storage of biogenic CO_2 (e.g., in wooden construction materials) represents the main challenge in the context of LCA of long-term CCU – our ongoing development of such a framework is likely to represent substantial progress in this context. Further, intrinsic uncertainties regarding end-of-life of products acting as temporary CO_2 storage and reaching their end of lifetime in decades from now makes LCA difficult and subject to subjective choices. We recommend developing LCI for a set of options of cascade use of wooden construction materials (including their potential end-of-life), as the construction sector seems to be one of the sectors with the highest potential for temporary storage of biogenic CO_2. A dynamic impact assessment approach, with a meaningful quantification of associated climate impacts, could be applied to such LCI.

Similar to the case of BECCS systems, the importance of including carbon dynamics in the forest supplying harvested wood for use as construction material must be stressed here (Strengers *et al.*, 2024).

5.3 LCA of further CDR methods to be evaluated in a consistent way

Within this project, we consider only a limited variety of novel CDR methods, focusing mainly on those which seem most relevant from a Swiss perspective today. However, as this field is growing rapidly, more CDR options are being developed and in the medium to long-term removing CO_2 abroad might gain importance for Switzerland. Thus, it would be valuable to gain an overview of this landscape of developing CDR options and evaluate which are most promising, also on an international level. As a part of this landscape, options that remove GHGs other than CO_2 should also be considered. Currently, methane removal technologies are at a very early stage of research, but in principle offer an opportunity to reduce the GHG concentration in the atmosphere (Jackson *et al.*, 2019; Lackner, 2020; Ming *et al.*, 2022; Sirigina, Goel and Nazir, 2022; Cobo *et al.*, 2023; Tao *et al.*, 2023; Wang and He, 2023). Marine CDR methods might deserve special attention, because while they offer in theory large CO_2 removal potentials, they are especially hard to monitor and verify (Boyd *et al.*, 2022; Cobo *et al.*, 2023; Mengis, Paul and Fernández-Méndez, 2023).

So far, only very few studies have compared the environmental performance of a range of CDR methods applying an LCA approach, and these studies only include a limited number of CDR methods with a focus on DACCS and BECCS (Chiquier *et al.*, 2022; Cobo *et al.*, 2022; Cooper, Dubey and Hawkes, 2022). Including the complete portfolio of CDR methods in a consistent setting is key for a meaningful comparison of their net carbon removal effectiveness and quantification of co-benefits and trade-offs regarding impacts on human health, ecosystems, and resources. Such a comparison should address at least some of the shortcomings of currently available LCA literature on CDR, for example the lack of considering regional boundary conditions by performing regionalized impact assessment, a lack of consistency when it comes to how to quantify climate impacts of non-permanent CO_2 removal, a lack of consistency regarding quantification of direct and indirect land use changes and associated climate impacts, and the way of how to deal with multi-functional systems, i.e., CDR methods which provide valuable products and services beyond CO_2 removal.

5.4 Prospective LCA

As the majority of CDR is likely to be implemented over the next decades, LCA should consider expected developments regarding both CDR as such as well as the economic background activities over this time frame. For example, in case of DACCS, among the most important factors for the life-cycle net CO_2 removal effectiveness are the carbon footprints of heat and electricity used for DAC operation and CO_2 compression, which often depends on the composition of the locally available electricity mix or specific sources of heat and electricity. The "premise" framework – which uses energy system or integrated assessment models and their scenario-specific trajectories to create consistent, prospective life cycle inventory databases – is a proper tool for such prospective LCA (Sacchi *et al.*, 2022). Important to note in case of prospective, comparative LCA of various CDR methods, consistency must be ensured. Here consistency refers to both the assumed pace of development of CDR methods as such, but also to the modification of the background inventory system, which can depend on socio-economic narratives, climate policy goals as well as the representation of technologies and economic sectors in in the underlying transformation pathways and scenarios of applied models (Sacchi *et al.*, 2022; Dekker *et al.*, 2023).

5.5 LCA embedded in a system analysis

The (environmental) impacts of CDR implementation most often depend on the scale of their employment because large-scale implementation will inevitably induce potentially undesired effects in the (national) economy and on the environment. As this work focuses on "single CDR units" and their LCA-based environmental impacts, quantified by attributional LCA, such large-scale system effects have not been investigated.[57] However, they should be. Such an analysis would ideally combine LCA, models of the (Swiss) energy system and models of the entire (Swiss) economy and thus consider resource constraints in terms of for example regionally available low-carbon power generation capacities, geological CO_2 storage capacities, water, land, and other potentially scarce resources, which would dynamically change over time and depend on climate policy ambitions. Such analysis on the system level would ideally include a large portfolio of CDR methods and allow to determine synergies or competition between single CDR methods employed in parallel. It would also allow to determine the most economic and most environmentally friendly climate policy in terms of reducing GHG emissions versus removing greenhouse gases from the atmosphere. It would also allow to identify the preferred way to use biomass, be it as construction material, to remove CO_2 from the atmosphere, or as energy carrier. Further, if performed at least on a European, but preferably on a global level, a system-wide analysis would also allow to determine best-suited regions for applying specific CDR methods, if their characterization considers regional differences, and to analyse the impact of CDR implementation on the energy system. Finally, embedding LCA of CDR methods in system analysis would allow to quantify marginal GHG removal cost curves, be it on a Swiss, European, or global level, and to establish marginal net-GHG removal effectiveness curves – both could represent valuable information for policy and investment decisions. One of the key shortcomings of available system-wide studies of CDR methods is that these are most often limited to few CDR methods, mainly

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[57] Nevertheless, the LCA results provided here and in section 4 as well as by the LCA tool developed are useful, as they provide a first good quantitative indication regarding possible net carbon removal efficiencies of several CDR methods in a Swiss context,, allow for conclusions regarding the conditions which must be met for the CDR methods addressed to provide effective net GHG removals from the atmosphere in general and can be used to identify key parameters in this respect. Further, LCI established are very well suited for follow-up activities as outlined in section 5.

forest related methods, BECCS, and DACCS (Strefler *et al.*, 2021; Cobo *et al.*, 2022; Dekker *et al.*, 2023; Fauvel *et al.*, 2023; Fuhrman *et al.*, 2023; Panos, Glynn, *et al.*, 2023). Efforts to overcome this limitation are on their way, e.g., as part of the Horizon Europe project "UPTAKE"[58].

Only a very limited number of studies linking LCA and some sort of system perspective have been performed so far. (Qiu *et al.*, 2022) performed comparative, prospective LCA of a few different DACCS configurations in a US-specific context, in which they quantified environmental co-benefits and trade-offs of CO_2 removal from the atmosphere under different boundary conditions. And (Fuhrman *et al.*, 2023) performed a global analysis on the role of different CDR methods (BECCS, DACCS, biochar, enhanced weathering, afforestation, and ocean based CDR) in future climate change mitigation scenarios in which they did not apply complete LCA, but took into account resource requirements of the CDR methods and regional constraints regarding their availability. Further, (Adun *et al.*, 2024) analysed the role of a broad set of CDR methods to achieve net-zero goals in Europe and found that the roles and individual contributions of specific CDR methods depend on boundary conditions such as ambitions in terms of GHG emission reduction, their timing, etc.

5.6 MRV and certification

The current MRV and certification landscape is fast paced, scattered and opaque. Implementation of CDR hinges on the ongoing research on quantification and monitoring approaches for different CDR methods. For land-based methods, there is a lot of potential for innovation in remote monitoring techniques, such as based on satellite data. Although this has been established for forestry, similar approaches for SCS are not yet well-established or proven (Smith *et al.*, 2024).

As most CDR projects currently partake in the voluntary carbon market (VCM), many certification processes and guidelines stem from here. Before CDR can be integrated into regulation, there is a need to establish a quality threshold for CDR methodologies. Credits must be high quality for the purpose of offsets. Due to the variety in TRL between different CDR methods and the high rate of innovation, a process much be derived to determine what level of uncertainty is acceptable for different CDR methods to be used as offsets. For CDR methods that cannot yet be used as offsets, alternative mechanisms should be in place to promote innovation.

Additionally, there is a need to improve the governance of the certification system. There is large variety in the methodologies and the scattered nature of the ecosystems creates resource inefficiencies. Evaluating the quality of current methodologies is time intensive, and the system is reported to be simultaneously not agile and not rigorous enough (Thorsdottir *et al.*, 2024). To incorporate CDR into regulatory mechanisms, a system must be in place that effectively and efficiently harmonizes current standards and updates it in line with research and technological advancements. Such a harmonization should include the recommendation to design MRV schemes based on consequential LCA methodology (Brander, 2024), as attributional LCA fails to quantify the total system-wide change in emissions and removals caused by an intervention or action.

5.7 Costs and potentials of CDR options

This work considers the environmental impact of different CDR options but does not yet consider the potential of these options. The cost and effectiveness of CDR options depend on the location; hence it is important to analyse this for the Swiss context. Most CDR options use scare resources such as land, biomass, or energy. Considering the current and projected availability of these resources in Switzerland, trade-offs will be necessary between different CDR options and with the larger Swiss system in which they operate. Alternatively, it could be considered to what extent it is feasible to rely on removals abroad, considering the attractiveness of this option for other countries as well.

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[58] https://www.cmcc.it/projects/uptake-bridging-current-knowledge-gaps-to-enable-the-uptake-of-carbon-dioxide-removal-methods (4.12.2023).

5.8 Financing of CDR

The scale-up of CDR relies heavily on investments, and even during operation, CDR options with little or no co-benefits such as DACCS, depend on the monetization of carbon removals. The financing of carbon removals remains an open question. The inherent difficulty of funding global public goods associated with large private costs will make it hard for future governments to share this burden among themselves. The lack of a clear business model for the private sector inhibits the scale-up as investors might be hesitant to get involved. For effective financing, what should the role of the government and the role of the private sector be? Who should pay upfront investments with uncertain revenue perspectives? Who should pay for potential needed insurance and accept liability? Currently, the voluntary carbon market provides a large role in financing CDR, but the lack of regulation and oversight make it difficult to provide reliable carbon offsets. Developing the right policy mix will also play an important role in enabling the financing of CDR. For example, (Lyngfelt, Fridahl and Haszeldine, 2024) recently proposed a concept which builds upon a CO_2 emitter liability operationalized through atmospheric CO_2 removal deposits – anyone emitting fossil CO_2 to the atmosphere would be obliged to finance the removal of at least as much CO_2 from the atmosphere.

5.9 Commercialization

To effectively scale up and commercialize CDR, it needs to be incentivized. (Hickey *et al.*, 2023) surveyed the policy mechanisms currently in place globally to incentivize CDR, together with an estimate of what different mechanisms are paying per ton of CO_2 removed, and how those costs are currently distributed. Their main finding is that “the majority of mechanisms currently in operation are under-resourced and pay too little to enable a portfolio of CDR that could support achievement of net zero” (Hickey *et al.*, 2023). Current mechanisms tend to support established afforestation and soil carbon sequestration methods, while in practice, alternative novel CER methods need to be scaled up to reach net-zero goals. Thus, a greater emphasis on policy innovation is needed as opposed to just focusing on technology development: What are the policies needed to incentivize scale up of novel CDR methods at the pace required to reach net zero? Which actors should take which roles? How can different public and private entities support commercialization of CDR methods in the best way?

In the context of CDR commercialization, it would also be important to get an overview about the currently quickly developing CDR start-up scene, for example regarding the representation of different CDR methods in the start-up ecosystem and the geographical distribution of CDR commercialization efforts. An evaluation of this start-up ecosystem would allow to identify beneficial boundary conditions and obstacles young companies are confronted with and to optimally support[59] and pave their way towards successful commercialization.

Finally, also the legal environment must be considered for future commercialization, e.g., regarding the legal liability of CO_2 removal (Ghaleigh and Macinante, 2023).

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[59] On the European level, “remove” (https://remove.global/) can be considered as a promising example of how to support CDR start-ups and accelerate their development.

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