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The Role of Atmospheric Carbon Dioxide Removal in Swiss Climate Policy

Fundamentals and Recommended Actions

August 2019

Commissioned by the Federal Office for the Environment (FOEN)

About this Report

This report is the result of a stakeholder risk dialogue on atmospheric greenhouse gas removal. Participants were invited from a broad range of institutions and include CDR practitioners, NGOs, federal offices and industry. The neutral and independent Risk Dialogue Foundation carried out the project between March 2018 and July 2019. The aim was to identify the current state of CDR options in Switzerland and identify recommendations for Swiss climate policy.

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About Risk Dialogue Foundation

The neutral and independent Risk Dialogue Foundation has 30 years of experience in the observation, analysis and moderation of risk dialogues, as well as in consultancy in risk analysis and communication. In addition, the foundation offers risk expertise and in-depth knowledge of specific risk related topics. The foundation initiates and moderates dialogues and offers a neutral platform for stakeholders to express their views.

Contents

Participating Stakeholders and Disclaimer

Participating Stakeholders

The following stakeholders have been part of the project:[1]

Karin Ammon	Swiss Academy of Natural Sciences SCNAT
Nino Berta	Climeworks
Urs Brodmann	First Climate Group
Bastien Girod	National Council – Green Party of Switzerland
Valentin Gutknecht	Neustark
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Cornelia Stettler	Myblueplanet
Darja Tinibaev	Foundation for Climate Protection and Carbon Offset KLiK
Martin Tschan	CemSuisse
Heiner Widmer	CemSuisse

[1] *Not all stakeholders have been able to participate in all main elements of the project (interviews, workshop 1, workshop 2, working group (authors)).*

Dominik Wlodarczak	JURA Management AG
Nikolaus Wohlgemuth	First Climate Group

As well as the project team at Risk Dialogue Foundation: Christoph Beuttler, Matthias Holenstein, Somara Gantenbein and Timothy Rüthi.

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Disclaimer

In line with views expressed during the dialogue, the objective of this report is to recommend actions for Swiss climate policy with a view to an open and public deliberation process and not to favour or promote any particular approaches. The views expressed in this report are solely those of its authors, and do not reflect any official positions, nor are they necessarily shared by all participating stakeholders in every detail – even though utmost care was taken to arrive at the largest possible consensus. At the beginning of the project, the project manager Christoph Beuttler also took up a position at one of the stakeholders, Climeworks. The Federal Office for the Environment (FOEN) and all participating stakeholders were informed of this prior to participation with no objections at all. The respective approach chapters have been largely written by stakeholders who are active in either research or (market) development of the respective approaches. The chapters were reviewed by all members of the working group, as well as participating experts from the FOEN and Swiss Federal Office of Energy (SFOE). Further, at the request of FOEN Risk Dialogue Foundation was asked to evaluate and describe uncertainties of technological potentials in the respective technology sections of chapter 2. During the course of the project, some stakeholders were otherwise engaged or changed positions. In these cases representatives of the respective organisation took part. Their names are listed individually above. This should not imply that some organisations/stakeholders had a more numerous representation than others. For further details of the project design, please see chapter 4.

Zusammenfassung – CDR-Ansätze in der künftigen Klimapolitik

Ausgangslage, wissenschaftliche Grundlage und internationaler Rahmen

Laut dem Intergovernmental Panel for Climate Change (IPCC) verlangt die Einhaltung des Übereinkommens von Paris eine schnellstmögliche Reduktion der CO_2-Emissionen auf netto null[1] bis spätestens 2050. Hierfür ist nach heutigem Wissensstand auch die aktive Entnahme von CO_2 aus der Atmosphäre nötig (Carbon Dioxide Removal CDR, oft auch negative Emissionen oder «Senken[2]» genannt).

Im fünften Sachstandsbericht des IPPC (IPCC AR5) basieren fast alle Szenarien, die zur Einhaltung des 2°C-Zieles führen, auf erfolgreichem CDR im Gigatonnen(Gt)-Massstab (siehe Abbildung 1). Für die Erreichung des 1.5°C-Zieles sind in allen Szenarien CDR-Ansätze eingerechnet. CDR-Ansätze werden auch benötigt, um unvermeidbare Emissionen etwa aus der Landwirtschaft oder der Zementproduktion zu neutralisieren. Im Mittel aller IPCC-Szenarien müssen bis zum Jahr 2100 kumulativ 630 Milliarden Tonnen CO_2-Emissionen wieder aus der Atmosphäre entfernt werden.[3] Zum Vergleich: Die Menschheit stösst gegenwärtig jedes Jahr etwa 40 Milliarden Tonnen CO_2-Äquivalente aus. Um eine entsprechende Grössenordnung mit CDR-Ansätzen zu erreichen, braucht es einen raschen und massiven Ausbau solcher Ansätze.

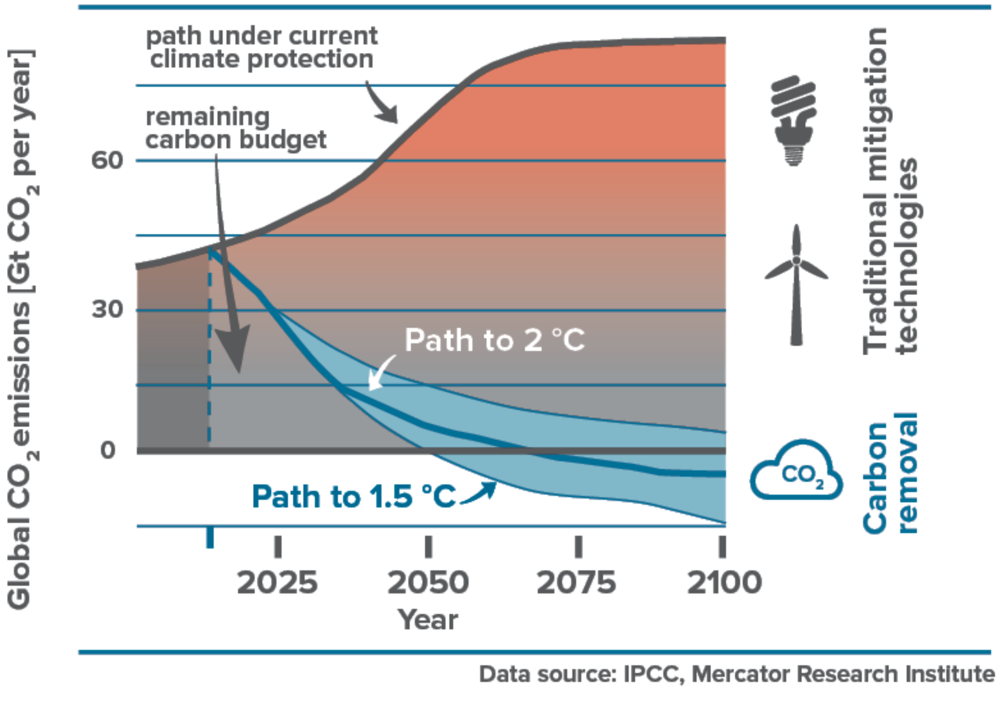

Abbildung 1. CDR ist notwendig für die Erreichung der Klimaziele des Pariser Übereinkommens[4]

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[1] *Gleichgewicht zwischen Emissionen und negativen Emissionen.*

[2] *Die technische Abscheidung von atmosphärischem CO_2 ist hier miteingeschlossen.*

[3] *IPCC AR5, 2014: IPCC, 'Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change' [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 2014, S. 151.*

[4] *Mercator Research Institute (MCC), 'Vorsicht beim Wetten auf Negative Emissionen: Neue Technologien sollen die CO2-Hypothek abbauen – trotz unsicherer Auswirkungen', MCC-Kurzdossier, Nr.2, 2016.*

Netto-Negative-Szenarien bis 2050 sind nur mit ambitionierter Mitigation bei gleichzeitiger Skalierung von CDR möglich

Eine CO_2-Neutralität ist unter Berücksichtigung der IPCC-Szenarien bis spätestens 2050 zu erreichen. Diese ist jedoch für die 1.5°C-Zielerreichung nur ausreichend, wenn dann bereits jährlich mindestens ca. 6 Gt CO_2 aus der Atmosphäre entfernt werden.[5] Ohne CDR müsste die globale CO_2-Neutralität sehr viel früher (ca. 2030) erreicht werden. Verspätet sich der Netto-Null-Zeitpunkt auf nach 2050, müsste CDR noch weiter ausgebaut werden. Es besteht also ein direkter Zusammenhang von CDR und Mitigation. In jedem Fall ist eine schnelle Skalierung von CDR notwendig. Beginnt die CDR-Skalierung erst im Jahr 2030 – wie es aktuell die internationale Politik vorsieht – wäre bereits ein jährliches globales Wachstum von 100% notwendig, um die benötigten Grössenordnungen zu erreichen.

Aufbau und Ziele des Projekts

Dieser Bericht ist das Ergebnis des Projekts «Stakeholderdialog zur Entfernung von Kohlenstoffdioxid aus der Atmosphäre (CDR)», welches die Stiftung Risiko-Dialog (SRD) zwischen März 2018 und Mai 2019 im Auftrag des Bundesamts für Umwelt (BAFU) durchführte. Daran nahmen mehr als 25 Stakeholder von verschiedenen NGOs, Behörden, Wissenschaften, der Wirtschaft und Politik teil. Basis war u.a. ein vorangehendes Dialogprojekt mit führenden Wissenschaftler/innen, welches 2017 abgeschlossen wurde.

Ziel des Projekts war, zuerst in der Schweiz ansässige Stakeholder mit Expertise im Bereich CDR resp. mit direkter Betroffenheit von der Anwendung von CDR zu identifizieren, um danach gemeinsam Chancen und Risiken mit Fokus auf der Schweiz zu bestimmen. Das Projekt nutzte die verfügbare Wissensbasis aller Beteiligten, um mit diesem Bericht das Verständnis in Bezug auf Governance, Kommunikation und Skalierung des CDR zu vertiefen. Schliesslich war das Ziel dieses Berichts, Massnahmen zur Minimierung möglicher CDR- und Klimarisiken sowie zur Nutzung von Chancen zu empfehlen.

Der Prozess des Stakeholderdialogs wurde wie folgt gestaltet. Nach der Einladung der Teilnehmenden führte die Stiftung Risiko-Dialog eine Reihe von Einzelinterviews mit Stakeholdern gemäss der Chatham-House-Regel durch, um maximale Meinungsfreiheit zu gewährleisten. Die Erkenntnisse aus den Interviews wurden in einem Informationspapier zusammengefasst, das allen Teilnehmenden vor dem ersten Workshop zugesandt wurde und als Grundlage dafür diente. Danach führte die SRD zwei eintägige Workshops mit allen Teilnehmenden durch, um die einzelnen Aspekte zu vertiefen und zu differenzieren. Schliesslich wurde eine Arbeitsgruppe gebildet, die diesen Bericht verfasste. Er wurde vor der Veröffentlichung von allen Teilnehmenden geprüft.

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[5] *G. F. Nemet, M. W. Callaghan, F. Creutzig, S. Fuss, J. Hartmann, J. Hilaire, W.F. Lamb, J.C. Minx, S. Rogers und P. Smith, 'Negative emissions – Part 3: Innovation and upscaling', Environmental Research Letters, Vol. 13, Nr. 6, 2018, S. 063003.*

Mögliche CDR-Ansätze in der Schweiz: Potentiale und Kosten

Die folgende Tabelle zeigt mögliche CDR-Ansätze, für welche in der Schweiz Stakeholder aktiv sind und die daher im vorliegenden Projekt berücksichtigt wurden.

Gruppe des CDR-Ansatzes	CDR-Ansatz
A) CDR durch Biomasse	A1. Afforestation and Forest Management
	A2. Improved Soil and Agricultural Management
	A3. Pflanzenkohle (Pyrogenic Carbon Capture and Storage and Use: PyCCS+U)
	A4. Bioenergy Utilisation in Combination with Carbon Capture & Storage (BECCS)
B) CDR durch technologische Ansätze	B1. Direct Air Capture (DAC)
C) CDR durch Enhanced Weathering	C1. Enhanced Weathering (über erhöhte Aufnahme in Zement)

Tabelle 2. Einteilung von CDR-Ansätzen in drei Hauptansätze.[6]

Die einzelnen Ansätze werden in den folgenden Kapiteln detailliert dargestellt. Zusammengefasst lassen sie sich wie folgt beschreiben: Afforestation and Forest Management (A1) umfasst das grossflächige Anpflanzen von Bäumen, um die Kapazität für Kohlenstoffspeicherung in Biomasse und Boden zu steigern. Improved Soil and Agricultural Management (A2) umfasst veränderte Bodenbewirtschaftung und Agrartechniken, die eine erhöhte CO_2-Aufnahme im Boden fördern und langfristig bewahren. Pflanzenkohle (Biochar, A3) wird durch Verbrennung von Biomasse ohne Sauerstoffzufuhr bei 400 bis 650°C erzeugt. Diese kann ausgebracht werden und den Anteil von Kohlenstoff im Boden langfristig erhöhen, vor allem in der Landwirtschaft. BECCS (A4) integriert Bioenergie mit geologischer Kohlenstoffspeicherung. Hierbei wird das CO_2, welches von Pflanzen aus der Luft gefiltert und bei der Verbrennung der Biomasse freigesetzt wird, aufgefangen und sequestriert. BECCS und Pyrolyse – das Herstellungsverfahren von Biochar – sind kombinierbar. Durch DAC (B1) wird das CO_2 technologisch direkt aus der Umgebungsluft gefiltert und anschliessend sequestriert. Enhanced Weathering via Zement (C1) beschreibt das chemische Binden von CO_2 sowie dessen Speicherung in Zement.

Basierend auf Angaben der Stakeholder (vergleiche Kapitel 2) und ergänzenden Hinweisen aus verfügbarer wissenschaftlicher Literatur gehen die Autoren/innen in Bezug auf die Senkenleistung von folgenden theoretischen Potentialen für 2050 innerhalb der Schweiz aus. Dabei wurden bei den einzelnen CDR-Ansätzen eher konservative Annahmen getroffen. Bei Afforestation and Forest Management (A1) wird gesamthaft von einer Senkenleistung von 3.1 Millionen Tonnen CO_2 pro Jahr ausgegangen, bei Improved Soil and Agricultural Management (A2) von jeweils 1.9 (Soil) und 1.7 (Agricultural) Millionen Tonnen CO_2 pro Jahr.[7] Für Biochar (A3) wird von 2.2 Millionen Tonnen CO_2 pro Jahr ausgegangen. Für BECCS (A4) liegen keine direkten Schätzungen vor. Die auf Biomasse basierenden Ansätzen konkurrieren jeweils mit weiteren CDR-Anwendungen oder bspw. Holzpro-

[6] *Akademien der Wissenschaften Schweiz, 'Emissionen rückgängig machen oder die Sonneneinstrahlung beeinflussen: Ist «Geoengineering» sinnvoll, überhaupt machbar und, wenn ja, zu welchem Preis?' Swiss Academies Factsheets, Vol. 13, Nr. 4, 2018.*

[7] *Diese dürften allerdings nach 20 Jahren sehr wahrscheinlich erschöpft sein.*

dukten. Die verfügbare Trockenbiomasse wird auf 2.8 Millionen Tonnen geschätzt, was eine Senkenleistung von 5.1 Millionen Tonnen CO_2 pro Jahr für BECCS ergäbe.[8] Dieses Potential könnte durch erfolgreiche Anwendung von A1-3 bis 2050 noch gesteigert werden. Für DAC (B1) ist theoretisch das gesamthaft verfügbare geologische Speicherpotential von 2.5 Milliarden Tonnen CO_2 verfügbar. Die dabei erreichbare CDR-Leistung hängt jedoch in höchstem Masse vom gesellschaftlichen und politischen Willen ab, eine entsprechende CO_2-Speicherung auch umzusetzen. Ebenso muss entsprechend inländisch erneuerbare Energie verfügbar sein. Das Potential von Enhanced Weathering (C1) via Zement liegt theoretisch bei 2.5 Millionen Tonnen CO_2 pro Jahr. Es hängt jedoch vom verfügbaren (atmosphärischen) CO_2 sowie der Menge an verfügbarem recycliertem Zement ab.

Nach ersten Schätzungen der Autoren/innen lässt sich aus diesen Angaben die Leistung aller CO_2-Senken für die Schweiz auf insgesamt rund 6 Millionen Tonnen CO_2 pro Jahr abschätzen, wobei im Sinne der Portfolio-Idee und einer Gesamtbilanz nicht überall alle genannten konservativen Annahmen berücksichtigt wurden. Die in der Schweiz bereits erprobten oder angewendeten Ansätze lassen vermuten, dass die dargestellten theoretischen Potenziale hier grundsätzlich zu realisieren sind. Die teilnehmenden Stakeholder haben bewusst auf eine vergleichende Darstellung der effektiv bis 2050 technisch und ökonomisch realisierbaren Potenziale verzichtet. Aufgrund des frühen Stadiums der CDR-Ansätze bestehen oft hohe Unsicherheiten in solchen Abschätzungen. Dies gilt insbesondere dort, wo noch wenig wissenschaftliche Publikationen vorliegen. In jedem Fall werden die identifizierten Potenziale wahrscheinlich durch verfügbare Biomasse, geologische Speicherungsmöglichkeiten, überwachbare Aufnahmekapazität im Boden oder Speicherungspotential bspw. in Zement, soziale Akzeptanz bei Lagerung oder Transport, verfügbare erneuerbare Energie oder durch die Realisierung der neuen land- oder forstwirtschaftlichen Praktiken indirekt begrenzt. Gerade für eine Lagerung ausserhalb der Schweiz ist zudem ein länderübergreifender politischer Wille nötig. Für alle Ansätze gilt, dass eine adäquate Regulierung für CDR (Carbon Pricing) und ein nahezu sofortiger koordinierte Ausbau der CDR-Ansätze bis 2050 und darüber hinaus nötig ist.[9] Dies ist selbstredend nur in Kombination mit einer ehrgeizigen Mitigationpolitik zu verstehen, bei der mindestens die Netto-Null-Ziele für 2050 verbindlich sind.

Dabei sind alle Ansätze bezüglich erwarteter Kosten, Risiken und verschiedener Nachhaltigkeitskriterien zu prüfen. Details hierzu finden sich im Kapitel 2. Bei der Afforestation and Forest Management (A1) werden Kosten von 1-100 Schweizer Franken pro Tonne (CHF/t) CO_2 geschätzt, wobei der Landverbrauch zu Risiken im Bereich Biodiversität und Ernährungssicherheit führen kann. Bei Improved Soil and Agricultural Management (A2) mit theoretisch 0-80 CHF/t CO_2 ist es fraglich, wie schnell solche Änderungen von Landwirten flächendeckend übernommen werden können. Bei Biochar (A3) rechnet man mit 10-135 CHF/t CO_2. Hier spielt vor allem die nachhaltig verfügbare Biomasse eine Rolle. Für BECCS (A4) werden Kosten von 50-250 CHF/t CO_2 geschätzt. Wie Biochar benötigt das Verfahren nachhaltige Biomasse, die mit einem geringen CO_2-Fussabdruck etwa durch Transport verfügbar ist. DAC (B2) ist von SCNAT mit 40-1000 CHF/t CO_2 prognostiziert, wobei der Stakeholder Climeworks die minimal möglichen Kosten auf 100 CHF/t schätzt. DAC weist einen sehr hohen Energiebedarf auf. Diese Energie muss zwingend erneuerbar sein, da sonst potentiell mehr CO_2 produziert als eingefangen wird. Für Enhanced Weathering (C1) liegen die Kosten bei 20-1000 CHF/t CO_2. Dabei gilt, dass bei Enhanced Weathering im eigentlichen Sinne bei Grosseinsätzen noch ungeklärte Auswirkungen bspw. auf die Wasserchemie (steigende pH-Werte) resultieren können. Bei der diskutierten Senke via Zement wird eine nachhaltige CO_2-Quelle (z.B. DAC) benötigt. Der Ansatz ist durch die verfügbare Menge an recycliertem Zement limitiert.

Generell gilt, dass sich viele der angesprochenen Risiken von CDR-Ansätzen erst bei grossskaligem Einsatz manifestieren. Um Risiken und Nachhaltigkeitskriterien besser einschätzen zu können, sind

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[8] O. Thees, V. Burg, M. Erni, G. Bowman und R. Lemm, 'Biomassenpotenziale der Schweiz für die energetische Nutzung', Ergebnisse des Schweizerischen Energiekompetenzzentrums SCCER BIOSWEET, WSL Bericht, Nr. 57, S. 299.

[9] In Anbetracht dessen wurde beschlossen, keine spezifische Angabe zu künftig realisierbaren Potentialen zu machen, um nicht den Eindruck zu hinterlassen oder die Kommunikation zu fördern, dass CDR „gelöst“ sei.

die einzelnen Ansätze weiter zu entwickeln und fortlaufend aus wissenschaftlicher Sicht zu evaluieren. Dabei ist ein gelebter Portfolio-Ansatz zentral: Aufgrund der vielen Unbekannten sind verschiedene CDR-Ansätze parallel zu entwickeln resp. zu erforschen. Zudem ist wichtig auch hier nochmals festzuhalten: CDR-Ansätze sind keine Alternative, sondern eine Ergänzung zu den Mitigationsmassnahmen.

Die Schweiz und CDR: Eine Chance für den Klimaschutz und den Wirtschaftsstandort Schweiz

Die Schweiz hat eine im globalen Vergleich sehr starke Position in diversen CDR-Anwendungen. Führend ist sie bereits in der Technologie Direct Air Capture (z.B. Climeworks). Ebenso ist die Schweiz in mehreren Elementen der Technologiewertschöpfungskette von Carbon Capture und Storage (CCS) aktiv (z.B. Sulzer, GE, ABB, MAN Energy Solutions, First Climate). Auch bei Biochar-Ansätzen ist sie gut aufgestellt. Diese Position kann die Schweiz nutzen, um (i) zur Reduktion von Klimarisiken beizutragen und (ii) CDR als einen der wichtigsten zukünftigen Nachhaltigkeitssektoren weltweit anzuführen. Bei einem CO_2-Preis von nur 100 US Dollar pro Tonne (USD/t) liegt das globale Marktpotenzial einer künftigen CDR-Industrie bei über 1000 Milliarden CHF. In Schweden z.B. kostet eine Tonne CO_2 schon jetzt um die rund 125 US Dollar, da das Land bis 2045 CO_2-neutral sein möchte. Um eine Führungsposition zu etablieren, sollte die Schweiz daher bereits heute einen entsprechenden Strukturwandel fördern.

Handlungsempfehlungen

Um die Klimaziele des Pariser Übereinkommens zu erreichen, ist es aus Sicht der Wissenschaft[10] und den im Projekt involvierten Stakeholdern aus den Bereichen NGOs, Behörden, Politik sowie Wirtschaft wichtig, sowohl natürliche als auch technologische Senken umgehend in das Klimaengagement der Schweiz zu integrieren. Gestützt auf die Ergebnisse dieses Berichts kommen die Autoren/innen zu folgenden Handlungsempfehlungen, die hier zusammenfassend dargestellt sind. Die umfassenden Handlungsempfehlungen finden sich in Kapitel 3 dieses Berichts.

Für die Klimapolitik der Schweiz

- Eine frühzeitige Verankerung von CDR-Ansätzen in der Klimapolitik der Schweiz (z.B. im CO_2-Gesetz) zeigt eine zukunftsgerichtete und verantwortungsvolle Haltung und fördert die öffentliche Auseinandersetzung. Als Nebeneffekt können sich CDR-Ansätze als langfristiger Wirtschaftsmotor für die Schweiz erweisen.
- Wirksame Massnahmen zur Emissionsminderung sind und bleiben der Schlüssel zu einer erfolgreichen Klimapolitik: Es empfiehlt sich, im Einklang mit den aktuellen Empfehlungen der Klimawissenschaft und des Pariser Übereinkommens die Treibhausgasemissionen auch der Schweiz so schnell wie möglich, mindestens aber im Jahr 2050 auf netto null zu senken. Um dies zu erreichen, müssen auch CDR-Ansätze entwickelt und evaluiert werden.

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[10] *Siehe Whitepaper aus dem vorhergehenden Wissenschaftsdialog: M. Honegger, S. Münch, A. Hirsch, C. Beuttler, T. Peter, W. Burns, O. Geden, T.Goeschl, D. Gregorowius, D. Keith, M. Lederer, A. Michaelowa, J. Pasztor, S. Schäfer, S. Seneviratne, A. Stenke, A. Patt und I. Wallimann-Helmer, 'Climate change, negative emissions and solar radiation management: It is time for an open societal conversation. White Paper by Risk Dialogue Foundation St.Gallen for the Swiss Federal Office for the Environment', 2017, www.risiko-dialog.ch/whitepaper.*

- CDR-Ansätze (Senken) sollten als Kompensationsmassnahmen, z. B. im Schweizer CO_2-Gesetz, anrechenbar sein. Denn eine frühe Finanzierung von CDR-Ansätzen über Kompensationsmechanismen kann die Skalierung zur Marktreife voranbringen, damit sie rechtzeitig im benötigten Wirkungsumfang bereitstehen. Langfristig müssen Kompensationsmechanismen im Hinblick auf eine CO_2-Neutralität 2050 sukzessive auf null reduziert werden, können jedoch bis dahin als Fördervehikel genutzt werden, um den Ausbau von CDR-Ansätzen voranzutreiben.
- Höhere CO_2-Steuer/Lenkungsabgaben auf Emissionen von fossilen Quellen – von mindestens 180 CHF/t sind nötig, um CDR-Ansätze zu entwickeln. Weiter sollte eine Anrechenbarkeit als Mitigationmechanismus auf technologische und natürliche Senken regulatorisch erwirkt werden (siehe vorheriger Punkt). Zum Vergleich, die CO_2-Steuer anderer Länder beträgt: Schweden 124 USD/t, Frankreich 51 USD/t und Grossbritannien 24 USD/t im 2019.[11] [12] [13]
- Um systemische Risiken im Hinblick auf Mitigation aber auch CDR zu reduzieren, ist die Klimapolitik mit Landwirtschafts-, Energie-, Raumplanungs- und Verkehrspolitik (evtl. über den Interdepartementalen Ausschuss IDA Klima und die Arbeitsgruppe Untergrund des Bundes) weiter zu koordinieren.
- Kantonale Klimapolitiken und Verordnungen sind auf eine allfällige Eidgenössische Netto-Null-Emissionspolitik 2050 abzustimmen.
- Die fachlichen Kompetenzen und Ressourcen im BAFU sind weiter zu stärken, um den Aufbau eines internen und externen Netzwerks zur Unterstützung von Politik und Verwaltung im Hinblick auf Netto-Null-Emissionen und CDR zu ermöglichen.
- Die führende Rolle der Schweiz in der internationalen Governanz soll dafür eingesetzt werden, dass
    - international eine adäquate CO_2-Bepreisung eingesetzt wird (CO_2-Steuern, CO_2-Abgaben und Emissionshandelssysteme).
    - eine evidenzbasierte, international abgestützte Diskussion und Entscheidungsfindung zum Einsatz und der Behandlung von CDR-Ansätzen erzielt wird.
    - Anpassungen und Zusätze der Londoner Konvention und des Londoner Protokolls der Internationalen Seeschifffahrts-Organisation durch die Vertragsparteien ratifiziert werden, um die Rahmenbedingungen für den grenzübergreifenden Einsatz von CCS zu verbessern und so grenzübergreifende CO_2-Speicherprojekte (auch im Sinne des Artikel 6 des Pariser Übereinkommens) zu ermöglichen.
- Im Pariser Übereinkommen müssen die Grundlagen für CDR erst noch geschaffen werden (Artikel 6). Generell ist die Frage der internationalen Anrechenbarkeit wichtig. Die Schweiz sollte sich hier auf internationaler Ebene engagieren und sich für klare Richtlinien einsetzen.

Für die Förderung (Forschung und Innovation, Markteinführung, Skalierung und Marktdiffusion) auf Bundes- und Kantonsebene

- Es sind zeitnah Rahmenbedingungen zu entwickeln, die für direkte Investitionsbeiträge und wirtschaftliche Anreize für CDR unter Berücksichtigung eines Portfolio-Ansatzes förderlich sind, um langfristige Ziele des Pariser Übereinkommens zu erreichen.
- Parallel ist ein nationaler Forschungsschwerpunkt für CDR (Grundlagenforschung) zu etablieren.
- Gleichzeitig soll der Ausbau der Förderungen für Prototypen, Pilote ab 2020 und Demonstrationen (idealerweise auch im Rahmen des CO_2-Gesetzes ab 2020) vorangetrieben werden.

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[11] *S. Postic und C. Métivier, 'Global Carbon Account 2019', Institute for Climate Economics (I4CE), 2019, www.i4ce.org/download/global-carbon-account-2019.*

[12] *Government Offices of Sweden, 'Sweden's carbon tax', 2019, www.government.se/government-policy/taxes-and-tariffs/swedens-carbon-tax.*

[13] *Ministry of the Environment, Energy and the Sea (MEEM), 'Le prix du carbone: Levier de la transition énergetique', 2016, www.ecologique-solidaire.gouv.fr/sites/default/files/prix-carbone_4p_DEF_Fr.pdf.*

- Eine begleitende Förderung der Skalierung von CDR-Ansätzen (Markteinführung und -diffusion im Rahmen des CO_2-Gesetzes, z.B. Technologiefonds, Stiftung KliK etc.) ist anzustreben.
- Für die Marktdiffusion soll die Entwicklung von Geschäftsmodellen unterstützt werden, welche neben der Entfernung von CO_2 aus der Atmosphäre auch marktfähige Produkte erzeugen können. So können die hohen Anfangskosten ausbalanciert werden, die CDR-Ansätze weiterentwickelt werden und zu einem späteren Zeitpunkt als CDR im eigentlichen Sinne ausgebaut werden.
- Bei Forschungsförderung, Entwicklung und Übernahme von CDR in den klimapolitischen Massnahmenkatalog ist auf Einklang mit den Sustainable Development Goals (SDG) zu achten.

Regulierung von CDR

- Die Schaffung auch von formalen Rahmenbedingungen für CDR ist wichtig. Die Schweiz sollte internationale Verträge, Konventionen und Protokolle unterstützen, die CDR-Ansätze beinhalten und ermöglichen. Zudem sollte sie eine angemessene CO_2-Preisgestaltung unterstützen. Dies kann auf allen Ebenen geschehen: CO_2-Steuern, CO_2-Abgaben und Emissionshandelssystem.
- Als Grundlage ist eine Verankerung von CDR in Eidgenössischen Gesetzen und Verordnungen (einschliesslich Aspekten wie Anrechenbarkeit, Förderung, Bewilligungen, Aufsicht) anzustreben.
- Auch auf der Verordnungsebene sollten Voraussetzungen für Anrechenbarkeit von Senken geschaffen werden: Pflanzenkohle (weil als Brennstoff klassifiziert) ist bspw. aktuell nicht anrechenbar oder geologische Senken werden in der aktuellen CO_2-Verordnung ausgeschlossen.
- Entwicklung von Monitoring-Massnahmen: Eine bedeutende Herausforderung, die sich beim Einsatz von CDR ergibt, ist die Sicherstellung und Überwachung der Permanenz der CO_2-Speicherung, gerade bei natürlichen Speichern (Holz und Boden).
- Alle Kohlenstoffsenken müssen unabhängig von Sektor und Technologie im nationalen Treibhausgasinventar abgebildet werden können.
- Die Messung, Berichterstattung und Überprüfung einer dauerhaften CO_2-Entfernung aus der Atmosphäre stellt Herausforderungen dar, insbesondere im Kontext der terrestrischen Senken. Es müssen pragmatische methodische Ansätze für Ökobilanzen geschaffen werden, ohne starke Einbussen bei der Abbildung des gesamten Lebenszyklus von CO_2-Emissionen und bei Senken in Kauf zu nehmen.
- Die Wahrung der Nachhaltigkeitskriterien ist bei allen CDR-Ansätzen sicherzustellen: So ist bspw. bei DAC sicherzustellen, dass (netto) auf erneuerbare Energien zum Betrieb der Anlagen zurückgegriffen wird. Für eine nachhaltige Entwicklung von Biomasse sind Schutzmassnahmen zu prüfen, um das Potenzial von BECCS und Biochar nutzen zu können. Es muss insbesondere die Konkurrenz mit dem Nahrungsmittelanbau sowie CO_2-neutralen Technologien, die Biomasse benötigen (z.B. Biogasanlagen und Holzwärmeverbünden), berücksichtigt werden.
- Planung und Überwachung der biophysikalischen Auswirkungen beim Einsatz von CDR: Bei landgestützten CDR-Optionen kann der Einsatz bspw. biophysikalische Auswirkungen[14] haben, die über die CO_2-Entfernung hinausgehen und eine entsprechende Überlegung erfordern.

[14] *Die Auswirkungen verschiedener Pflanzen auf die Albedo, z.B. erhöhte Erwärmung bei Aufforstung durch dunklere Waldflächen siehe: P. Smith et al., 'Biophysical and economic limits to negative CO_2 emissions', Nature climate change, vol. 6, no. 1, 2016, p. 42.*

Gesellschaftspolitische Rahmenbedingungen und Chancen

- Es ist ein breites öffentliches Bewusstsein für und eine vertiefte Auseinandersetzung mit CDR-Ansätzen zu fördern: Ein gesellschaftlicher Dialog basierend auf wissenschaftlichen Erkenntnissen ist notwendig, damit die Bevölkerung letztendlich fundierte Entscheidungen zum Einsatz von CDR treffen kann. Dazu gehört auch das Aufzeigen der Dringlichkeit des Themas der Klimaveränderung und der Notwendigkeit zur schnellen Umsetzung verschiedener Massnahmen (Mitigation, CDR).
- Eine präzise Sprache in der Kommunikation sowie in jeglicher Vorbereitung für eine öffentliche Debatte ist zu nutzen. Eine Diskussion über CDR unter generischen Bezeichnungen wie etwa Geoengineering ist zu vermeiden, da diese Bezeichnungen zwei fundamental unterschiedliche Ansätze und Risikoprofile kombinieren und daher nicht effektiv sind. Die Diskussion von Risiken, Chancen, Potentialen etc. erfordert eine klare Definition der einzelnen Ansätze.
- Die aktuellen Risikoeinschätzungen zeigen, dass das Wissen um CDR-Ansätze auch in der Politik, Industrie und Zivilgesellschaft – gemessen an der Faktenlage – noch zu wenig etabliert ist. Aus Sicht von CDR-Experten/innen ist eine baldige intensive Diskussion zur Umsetzung unabdingbar. Um diese zu unterstützen und um neben der Wissenschaft noch weitere Stakeholder zu integrieren, bietet sich ein breiter Stakeholderdialog zwischen öffentlicher Hand, Industrie, NGOs und weiteren Interessensgruppen auf nationaler Ebene. In solch einem fokussierten Dialogprozess sollten Schweizer und internationale Klimaforscher/innen und Policy-Fachleute zusammen mit Fachämtern, wie bspw. dem BAFU oder kantonalen Behörden, Rahmenbedingungen, Möglichkeiten und Umsetzungsthemen einer konkreten Dekarbonisierungsstrategie 2050 gestalten. Weitere Stakeholder wie Politik, Industrie und Zivilgesellschaft sind fortlaufend zu integrieren. Eine gemeinsame Aushandlung von konkreten Vorschlägen im Umgang mit CDR dient auch der politischen Entscheidungsfindung.
- Die Diskussion um die Eindämmung der Klimakrise muss auch aufzeigen, wie die Akzeptabilität technischer Lösungen insbesondere auch für Speichermöglichkeiten von CO_2 erzielt wird. Nur so wird eine langfristige und breit getragene Umsetzung möglich sein.
- CDR-Ansätze sind ein Wirtschaftszweig mit erheblichem Wachstumspotential. Gelingt es der Schweiz, ihre führende Rolle zu behalten, kann dies wirtschaftlich Vorteile bringen und den hiesigen Standort fördern. Neben den bereits gezeigten Ansätzen können wettbewerbsfähige Power-to-X-Technologien (PtX, z.B. Synfuels) abgeschiedenes CO_2 durch Umwandlung in nützliche Produkte verwerten, Luftverschmutzung reduzieren und die Schweiz von volatilen (Energie-)Importmärkten unabhängig machen sowie die Versorgungssicherheit erhöhen. Neben erneuerbarer Energie wird dafür vor allem erneuerbares CO_2 aus der Atmosphäre benötigt. Ein Ausbau von PtX würde daher auch die Skalierung von CDR fördern.

Insgesamt bieten die verschiedenen CDR-Ansätze eine zukunftsgerichtete Option, welche weiter in der nötigen Geschwindigkeit zu entwickeln und im Sinne eines Portfolio-Ansatzes in Bezug auf Nutzen und Gefahren zu evaluieren sind. Sie sind dabei kein Ersatz, sondern eine Ergänzung zu allen Mitigationsmassnahmen, um eine zu starke Klimaerwärmung zu vermeiden.

Summary – CDR Approaches in Future Climate Policy

Initial Situation, Scientific Basis and International Setting

According to the Intergovernmental Panel for Climate Change (IPCC), compliance with the Paris Agreement requires the fastest possible reduction of CO_2 emissions to net zero[1] by 2050 at the latest. According to the current state of knowledge, this requires as well the active removal of CO_2 from the atmosphere (carbon dioxide removal CDR, often called negative emissions or «sinks[2]»).

In the Fifth Assessment Report of the IPPC (IPCC AR5), almost all of the scenarios leading to compliance with the 2°C target are based on successful CDR on a gigatonnes (Gt) scale (see Figure 1). To achieve a 1.5°C target, CDR approaches are included in all scenarios. CDR approaches are also needed to neutralise unavoidable CO_2 emissions from e.g. agriculture or cement production. On average for all IPCC scenarios, 630 billion tonnes of CO_2 emissions must be cumulatively removed from the atmosphere by 2100.[3] By way of comparison, humanity emits about 40 billion tonnes of CO_2 eq. every year. In order to achieve a corresponding magnitude with CDR approaches, a rapid and massive expansion of such approaches is needed.

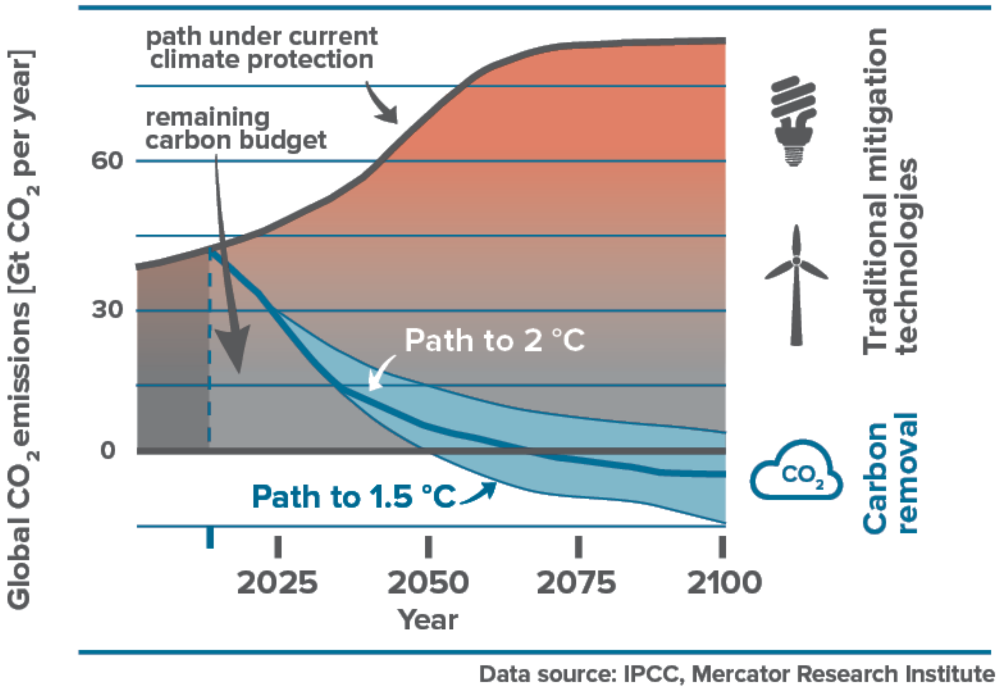

Figure 1. How to keep global warming below 2 °C.[4]

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[1] *Balance between emissions and negative emissions.*

[2] *Technical separation of atmospheric CO_2 is included here.*

[3] *IPCC AR5 see: IPCC, 'Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change' [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 2014, pp. 151.*

[4] *Mercator Research Institute (MCC), 'Vorsicht beim Wetten auf Negative Emissionen: Neue Technologien sollen die CO_2-Hypothek abbauen – trotz unsicherer Auswirkungen', MCC-Kurzdossier, no.2, 2016.*

Net Zero Scenarios Until 2050 Are Only Possible with Ambitious Mitigation with Scaling of CDR at the Same Time

CO_2 neutrality must be achieved by 2050 at the latest, taking into account all IPCC scenarios. However, to achieve the 1.5°C target, this is only sufficient if at least 6 Gt CO_2 are removed from the atmosphere every year.[5] If CDR approaches are omitted, global CO_2 neutrality needs to be achieved much earlier, around 2030. If the net zero point is later than 2050, CDR would have to be further expanded. Thus, there is a direct correlation between CDR and mitigation. In any case, fast scaling of CDR is necessary. If CDR scaling does not start until 2030 – as currently stipulated by international politics – an annual global growth of 100% would be necessary to reach the required levels.

Design and objectives of the project

This report is the result of a stakeholder dialogue project on atmospheric carbon dioxide removal (CDR), which the Risk Dialogue Foundation (RDF) conducted between March 2018 and May 2019. For this project, more than 25 stakeholders from different NGOs, government agencies, sciences, industries and politics took part in this project, which was commissioned by the Federal Office of the Environment (FOEN). Basis was, amongst other things, a previous dialogue project with leading scientists in the field, which was concluded in 2017.

The aim of the project was to first identify Switzerland based stakeholders with expertise in CDR, or representing those affected by it. This in order to identify opportunities and risks around CDR with a focus on Switzerland. The project utilised the available knowledge base to deepen the understanding of many aspects related to governance, communications, and scale up around CDR with this report. Finally the aim of this report was to recommend actions on how to minimise CDR and climate risks and maximise opportunities of CDR.

The process of the stakeholder dialogue was designed as follows. After the invitation of participants, RDF conducted a series of one-on-one interviews with stakeholders under Chatham House rules to ensure maximum freedom of expression. The insights from the interviews were combined in a briefing paper which was sent to all participants before the first workshop and served as its basis. Thereafter RDF ran two one-day workshops with all participants in Zurich. Finally, a working group was formed that authored this report which was reviewed by all participants before publication.

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[5] *G. F. Nemet, M. W. Callaghan, F. Creutzig, S. Fuss, J. Hartmann, J. Hilaire, W.F. Lamb, J.C. Minx, S. Rogers und P. Smith, 'Negative emissions – Part 3: Innovation and upscaling', Environmental Research Letters, Vol. 13, Nr. 6, 2018, p. 063003.*

Possible CDR Approaches in Switzerland: Potentials and Costs

Table 2 shows possible CDR approaches for which Swiss stakeholders are active and which were therefore taken into account in this project.

Group of CDR Approach	CDR Approach
A) CDR via biomass	A1. Afforestation and forest management
	A2. Improved soil and agricultural management
	A3. Biochar (Pyrogenic carbon capture and storage and use: PyCCS+U)
	A4. Bioenergy utilization in combination with carbon capture & storage (BECCS)
B) CDR via technological approaches	B1. Direct air capture (DAC)
C) CDR via enhanced weathering	C1. Enhanced weathering (via enhanced uptake in cement)

Table 2. Categorisation of CDR approaches into three main approaches.[6]

The individual approaches are described in detail in the following chapters. In summary, they can be described as follows: Afforestation (A1) involves the large-scale planting of trees in order to increase the capacity for carbon storage in biomass and soil. Improved soil and agricultural management (A2) involves altered land management and agricultural techniques that promote increased CO_2 uptake in soil and preserve it long term. Biochar (A3) is produced by combustion of biomass without supply of oxygen at 400 to 650°C. This can be spread and thus increase the proportion of carbon in the soil in the long-term, especially in agriculture. BECCS (A4) integrates bioenergy with geological carbon storage. Here, the CO_2 – which is filtered by plants from the air and released during the combustion of biomass – is collected and sequestered. BECCS and pyrolysis – the production process of biochar – can be combined. Through DAC (B1) CO_2 is technologically directly filtered from the ambient air and afterwards sequestrated. Enhanced weathering via cement (C1) describes the chemical bonding of CO_2 and its storage in cement.

Concerning the carbon sink capacity, based on information of the stakeholders (see chapter 2) and additional evidences from available scientific literature the authors assume the following theoretical potentials for 2050 within Switzerland. Whereas rather conservative assumptions have been made for the individual CDR approaches. For afforestation (A1), a total carbon sink capacity of 3.1 million tonnes CO_2 per year is assumed, for improved soil and agricultural management (A2) 1.9 (soil) and 1.7 (agricultural) million tonnes CO_2 per year are estimated.[7] Biochar (A3) is expected to produce 2.2 million tonnes CO_2 per year. For BECCS (A4) no direct estimates are available. Approaches based on biomass compete with other CDR approaches or, e.g. wood products. The available dry biomass is estimated at 2.8 million tonnes, which would account for 5.1 million tonnes CO_2 per year of carbon sink capacity for BECCS.[8] This potential could be further increased by successful application of A1-3 until 2050. For DAC (B1), the total of available geological storage potential of 2.5 billion

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[6] *Akademien der Wissenschaften Schweiz, 'Emissionen rückgängig machen oder die Sonneneinstrahlung beeinflussen: Ist «Geoengineering» sinnvoll, überhaupt machbar und, wenn ja, zu welchem Preis?' Swiss Academies Factsheets, vol. 13, no. 4, 2018.*

[7] *However, these are most likely to be exhausted after 20 years.*

[8] *O. Thees, V. Burg, M. Erni, G. Bowman und R. Lemm, 'Biomassenpotenziale der Schweiz für die energetische Nutzung', Ergebnisse des Schweizerischen Energiekompetenzzentrums SCCER BIOSWEET, WSL Bericht, no. 57, p. 299.*

tonnes CO_2 is theoretically available. However, the achievable CDR performance depends to a great extent on the social and political will to implement a corresponding CO_2 storage. Similarly, locally renewable energy must be available. The potential of enhanced weathering via cement (C1) is theoretically 2.5 million tonnes CO_2 per year. However, it depends on the available (atmospheric) CO_2 as well as the amount of available recycled cement.

According to initial estimates by the authors, this information can be used to estimate the performance of all CO_2 sinks for Switzerland at a total of around 6 million tonnes of CO_2 per year – whereas in the sense of a portfolio idea and an overall balance not all the mentioned conservative assumptions were taken into account. Approaches already tested or applied in Switzerland suggest that the illustrated theoretical potentials are basically attainable. The participating stakeholders have deliberately renounced a comparative presentation of the potentials that can be effectively realised by 2050 in terms of technology and economics. Due to the early stage of CDR approaches, there are often high uncertainties in such estimations. This is especially true where there are still few scientific publications available. In any case, the identified potentials are likely to be indirectly limited due to available biomass, geological storage potentials, monitorable absorption capacity in soil or storage potential e.g. in cement, social acceptability during storage or transport, available renewable energy or the realisation of new agricultural or forestry practices. Especially for storage outside of Switzerland a transnational political will is required. For all approaches, adequate regulation for CDR (carbon pricing) and an almost immediately coordinated expansion of CDR approaches by 2050 and beyond are needed.[9] This, of course, can only be understood in combination with an ambitious mitigation policy in which at least the net zero targets for 2050 are binding.

All approaches need to be examined regarding expected costs, risks and various sustainability criteria. Details can be found in chapter 2. For afforestation (A1) costs of 1-100 Swiss francs per tonne (CHF/t CO_2) are estimated, whereby land use can lead to risks in the area of biodiversity and food security. In the case of improved soil and agricultural management (A2) with theoretically 0-80 CHF/t CO_2, it is questionable how quickly such changes can be area-widely implemented by farmers. Biochar (A3) is expected to cost 10-135 CHF/t CO_2. Here, especially the sustainably available biomass plays a role. For BECCS (A4) costs of 50-250 CHF/t CO_2 are estimated. Like Biochar, the process requires sustainable biomass that is available with a low carbon footprint, such as through transportation. DAC (B2) is forecasted by SCNAT at 40-1000 CHF/t CO_2, with the stakeholder Climeworks estimating the minimum possible cost at 100 CHF/t. DAC has a very high energy demand. This energy must therefore necessarily be renewable, otherwise potentially more CO_2 is produced than captured. Enhanced weathering (C1) costs around 20-1000 CHF/t CO_2. It should be noted that in the case of enhanced weathering – when used on a large scale – unexplained effects can result, e.g. on water chemistry (increasing pH values). The discussed sink via cement requires a sustainable source of CO_2 (e.g. DAC). The approach is limited by the amount of recycled cement available.

As a general rule, many of the risks mentioned only manifest themselves when CDR approaches are used on a large scale. In order to better understand these risks as well as sustainability criteria, the individual approaches need to be further developed and continuously evaluated. In doing so, a portfolio approach is central: due to the many unknowns, various CDR approaches must be developed or researched in parallel. In addition, it is important to keep in mind that CDR approaches are not an alternative but a complement to mitigation efforts.

[9] *Considering this, it was decided not to make any specific statement of realisable future potentials so as not to leave the impression or encourage communication that CDR was "solved".*

Switzerland and CDR: An Opportunity for Climate Protection and Switzerland as a Business Location

In global comparison, Switzerland has a very strong position in various CDR approaches. It is already leading in the technology of direct air capture (DAC, e.g. Climeworks). Furthermore, Switzerland is also active in other elements of the technology value chain of carbon capture and storage (CCS, e.g. Sulzer, GE, ABB, MAN Energy Solutions, First Climate) and well positioned for biochar approaches. Switzerland can use this position to (i) contribute to reducing climate risks and (ii) lead CDR as one of the most important future sustainability sectors worldwide. With a CO_2 price of only 100 US dollars per tonne (USD/t), market potential of a future CDR industry is over 1000 billion CHF. In Sweden, e.g. a tonne of CO_2 now costs about 125 US dollars, as the country wants to be CO_2 neutral by 2045. In order to establish a leading position, Switzerland should therefore already promote a corresponding structural change today.

Recommendations for Action

From the point of view of science[10], as well as the stakeholders involved in the project, NGOs, authorities, politics and industry, it is important to integrate natural and technological sinks immediately into Switzerland's climate engagement in order to achieve the climate goals of the Paris Agreement. Based on the results of this report, the authors come to the following recommendations for action, which are summarised here. Comprehensive recommendations for action can be found in chapter 3 of this report.

For Switzerland's climate policy

- An early embedding of CDR approaches in Switzerland's climate policy (e.g. in the CO_2 Act) shows a forward-looking and responsible attitude, and promotes a public debate. As a side effect, CDR approaches could prove to be a long-term economic engine for Switzerland.
- Effective measures to reduce emissions are and will remain key to a successful climate policy: in line with the current recommendations of climate science and the Paris Agreement, it is advisable to reduce Switzerland's emissions to net zero as quickly as possible, but at latest by 2050. To achieve this, CDR approaches must also be developed and evaluated.
- CDR approaches (sinks) should be creditable as compensation measures, e.g. in the Swiss CO_2 Act. This is because early financing of CDR approaches through compensation mechanisms can advance scaling to a marketable size so that they are available in the required extent in time. In the long term, compensation mechanisms must be successively reduced to zero with a view to CO_2 neutrality by 2050, but can still be used until then to advance CDR approaches.
- Higher CO_2 tax/incentive levies on emissions from fossil sources – at least 180 CHF/t are needed to develop CDR approaches. Furthermore, crediting as a mitigation mechanism to regulatory and

[10] *See Whitepaper from the previous science dialogue: M. Honegger, S. Münch, A. Hirsch, C. Beuttler, T. Peter, W. Burns, O. Geden, T.Goeschl, D. Gregorowius, D. Keith, M. Lederer, A. Michaelowa, J. Pasztor, S. Schäfer, S. Seneviratne, A. Stenke, A. Patt and I. Wallimann-Helmer, 'Climate change, negative emissions and solar radiation management: It is time for an open societal conversation. White Paper by Risk Dialogue Foundation St.Gallen for the Swiss Federal Office for the Environment', 2017, www.risiko-dialog.ch/whitepaper.*

natural sinks should be effected (see previous point). For comparison, CO_2 taxes of other countries: Sweden about 124 USD/t, France about 51 USD/t and Great Britain about 24 USD/t in 2019.[11] [12] [13]

- In order to reduce systemic risks with regard to mitigation but as well CDR, climate policy must be further coordinated with agricultural, energy, spatial planning and transport policy (possibly via the Interdepartmental Committee IDA Climate and the Federal Underground Working Group).
- Further, cantonal climate policies and ordinances must also be coordinated for a potential federal net zero emissions policy 2050.
- Professional competencies and resources of the FOEN must be further strengthened. This in order to enable the establishment of an internal and external network to support policy and administration with regard to net zero emissions and CDR.
- Switzerland's leading role in international governance should be used to ensure that
  - an adequate CO_2 pricing is developing internationally (CO_2 taxes, CO_2 levies and emissions trading scheme).
  - an evidence-based, internationally supported discussion and decision-making on the use and treatment of CDR approaches is achieved.
  - adaptations and additions to the London Convention and the London Protocol of the International Maritime Organisation will be ratified by the contracting parties in order to improve the framework conditions for the cross-border deployment of CCS and thus enable cross-border CO_2 storage projects (also within the meaning of Article 6 of the Paris Agreement).
- The Paris Agreement first needs to lay the foundations for CDR (Article 6). In general, the question of international creditability is important. Here, Switzerland should be engaged on an international level and stand up for clear guidelines.

For funding (research and innovation, market introduction, scaling and market diffusion) at federal and cantonal level

- As a requirement, near-term framework conditions must be developed for direct investments and economic incentives for CDR, taking into account a portfolio approach to achieve the long-term targets of the Paris Agreement.
- Parallel, a national research focus for CDR (basic research) is to be established.
- At the same time, the expansion of funding for prototypes, pilots from 2020 on and demonstrations (ideally also within the framework of the CO_2 Act starting 2020) is to be promoted.
- An accompanying promotion of the scaling of CDR approaches (market introduction and diffusion within the framework of the CO_2 Act, e.g. technology funds, KliK Foundation, etc.) is to be aimed for.
- For market diffusion, the development of business models should be supported which – in addition to removing CO_2 from the atmosphere – will produce a marketable product. In this way high initial costs can be balanced, the CDR approaches can be further developed and at a later time expanded as CDR in the actual sense.
- For research funding, development and integration of CDR in the mitigation catalog of measures, it is important to ensure compliance with the Sustainable Development Goals (SDG).

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[11] S. Postic and C. Métivier, 'Global Carbon Account 2019', Institute for Climate Economics (I4CE), 2019, www.i4ce.org/download/global-carbon-account-2019.

[12] Government Offices of Sweden, 'Sweden's carbon tax', 2019, www.government.se/government-policy/taxes-and-tariffs/swedens-carbon-tax.

[13] Ministry of the Environment, Energy and the Sea (MEEM), 'Le prix du carbone: Levier de la transition énergetique', 2016, www.ecologique-solidaire.gouv.fr/sites/default/files/prix-carbone_4p_DEF_Fr.pdf.

Regulation of CDR

- Governance of CDR is important. Switzerland should support international treaties, conventions and protocols that include and enable CDR approaches. Further, it should support the use for adequate CO_2 pricing. This can happen on all levels: CO_2 taxes, CO_2 levies and emissions trading system.
- As a basis, CDR should be embedded in federal laws and ordinances (including aspects such as accounting, promotion, permits, supervision).
- On an ordinance level as well, conditions for the accounting of sinks should be created: for example, plant carbon (because classified as fuel) is currently not taken into account or geological sinks are neglected.
- Development of monitoring measures: An important challenge posed by the use of CDRs is the ensuring and monitoring of the permanence of CO_2 storage, especially in the case of natural storages (wood and soil).
- All carbon sinks – regardless of sector or technology – must be mapped in the national greenhouse gas inventory.
- Measuring, reporting and verifying permanent CO_2 removal from the atmosphere poses challenges, especially in the context of terrestrial sinks. Pragmatic methodological approaches for ecological assessments need to be created without accepting major losses in the mapping of the entire life cycle of CO_2 emissions and sinks.
- Compliance with sustainability criteria must be ensured in all CDR approaches: For example, it must be ensured that for DAC (net) renewable energy is used to operate the plants. Protective measures need to be examined for the sustainable development of biomass in order to exploit the potential of BECCS and biochar. In particular, competition with food cultivation and CO_2 neutral technologies that require biomass (e.g. biogas plants and wood-fired heating systems) must be taken into account.
- Planning and monitoring of biophysical effects of CDR: With land-based CDR options, an application can have e.g. biophysical effects[14], which go beyond CO_2 removal and require appropriate consideration.

Sociopolitical conditions and opportunities

- A broad public awareness and an in-depth examination of CDR approaches should be promoted: a social dialogue based on scientific knowledge is necessary so that society can ultimately make well-founded decisions about the use of CDR. This also includes highlighting the urgency of the issue of climate change and the need for rapid implementation of various measures (mitigation, CDR).
- A precise language in communication and in any preparation for public debate is recommended. Discussions of CDR under generic terms such as geoengineering should be avoided because they combine two fundamentally different approaches and risk profiles and are thus not effective. The discussion of risks, opportunities, potentials etc. requires a clear definition of each of the approaches.
- The current risk assessments show that knowledge of CDR approaches in politics, industry and civil society – measured by the facts – is still too little established. From the point of view of CDR experts, an in-depth discussion on implementation is indispensable. In order to support them and to integrate other stakeholders in addition to science, a broad stakeholder dialogue between public sector, industry, NGOs and other interest groups at the national level would be a fitting way. In such a focused dialogue process, Swiss and international climate researchers and policy

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[14] *Effects of various plants on the albedo, e.g. increased heating due to afforestation through darker woodlands see: P. Smith et al., 'Biophysical and economic limits to negative CO_2 emissions', Nature climate change, vol. 6, no. 1, 2016, p. 42.*

experts together with specialist offices such as the FOEN or cantonal authorities, should shape framework conditions, possibilities and implementation topics of a concrete 2050 decarbonisation strategy. Further stakeholders such as politics, industry and civil society need to be integrated on an ongoing basis. A joint negotiation of concrete proposals in dealing with CDR also serves the political decision-making process.

- The discussion about the climate crisis must also show how acceptability of technical solutions can be achieved, especially for CO_2 storage options. Only in this way a long-term and broad-based realisation will be possible.
- CDR approaches are an economic sector with considerable growth potential. If Switzerland succeeds in maintaining its current leading role, this can bring economic advantages and promote its attractiveness for industy and commerce. In addition to the approaches already shown, competitive PtX technologies (Power-to-X, e.g. Synfuels) can convert captured CO_2 into useful products, reduce air pollution and make Switzerland independent of volatile (energy) import markets. In addition to renewable energy, renewable CO_2 from the atmosphere is needed. An expansion of PtX would therefore also promote the scaling of CDR.

Overall, various CDR approaches offer a future-oriented option which must be further developed at the necessary speed and evaluated in terms of benefits and risks in line with a portfolio approach. At the same time, they are not a substitute but an addition to all mitigation measures to avoid excessive global warming.

1 Climate Risk, Mitigation and CDR – Current State of Affairs

In the 2015 landmark Paris Agreement[1], the international community committed to limit global warming by the year 2100 to “well below 2°C” and to pursue efforts to keep warming below 1.5°C compared to pre-industrial levels.

However, rather than a rapid decline toward zero emissions, annual greenhouse emissions continue to rise, rendering these goals increasingly hard to achieve and near impossible with emissions reductions alone. Hence, atmospheric carbon dioxide removal (CDR) often also called negative emissions technologies (NETs) have increasingly been included in the vast majority of mitigation pathways and are necessary to limit global warming to 2°C and even more so to 1.5°C.

According to all 1.5°C[2] and almost all 2°C scenarios, net zero CO_2 emissions must be reached by mid-century, followed by a period of net-negative emissions – meaning that CDR rates exceed residual emissions (IPCC AR5 2014[3], IPCC SR15 2018[4]). In most scenarios the rate of past emissions which will need to be removed through CDR reaches several billions of tonnes (1Gt = 1 billion tonnes) per year after 2025 for 1.5°C or after around 2040 for 2°C. This needs to be maintained for several decades over several decades as shown in Figure 1 (blue part).

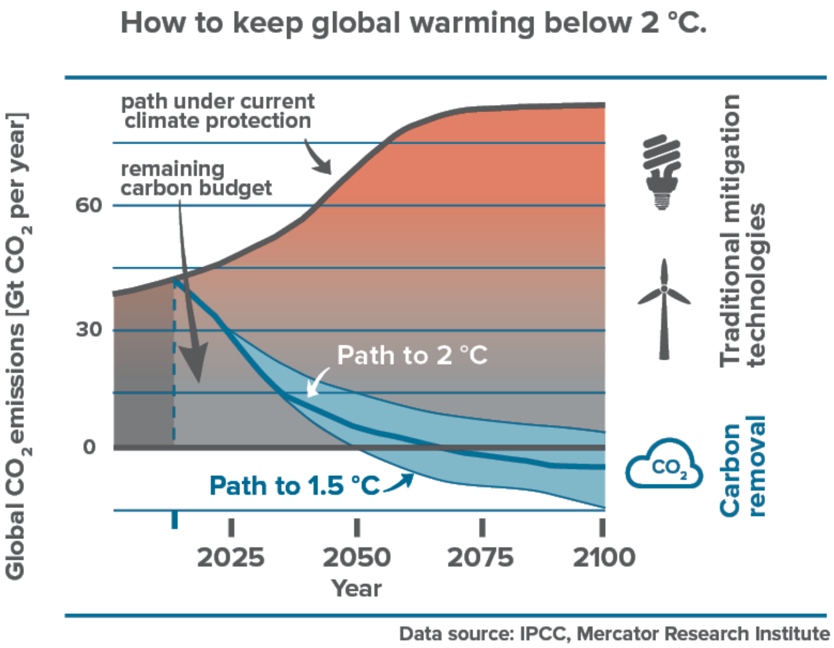

Figure 1. How to keep global warming below 2 °C.[5]

[1] UNFCCC, 'Paris Agreement', 2015.

[2] All scenarios in the IPCC AR5 and all in the IPCC SR15 are without overshoot (overshoot being nothing other than not sticking to 1.5°C)

[3] IPCC AR5, 2014: IPCC, 'Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change', IPCC, Geneva, Switzerland, 2014, pp. 151.

[4] *IPCC SR15, 2018: IPCC, 'Summary for Policymakers. In:* Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*',* World Meteorological Organization, Geneva, Switzerland, *2018,* pp. 32.

[5] *Mercator Research Institute (MCC), 'Vorsicht beim Wetten auf Negative Emissionen: Neue Technologien sollen die CO2-Hypothek abbauen – trotz unsicherer Auswirkungen', MCC-Kurzdossier, no.2, 2016.*

Those scenarios that attempt to limit global warming to 1.5 or 2°C without such a period of net-negative emissions only achieve this by an even more dramatic pace of emission phase-out as shown in Figure 2.

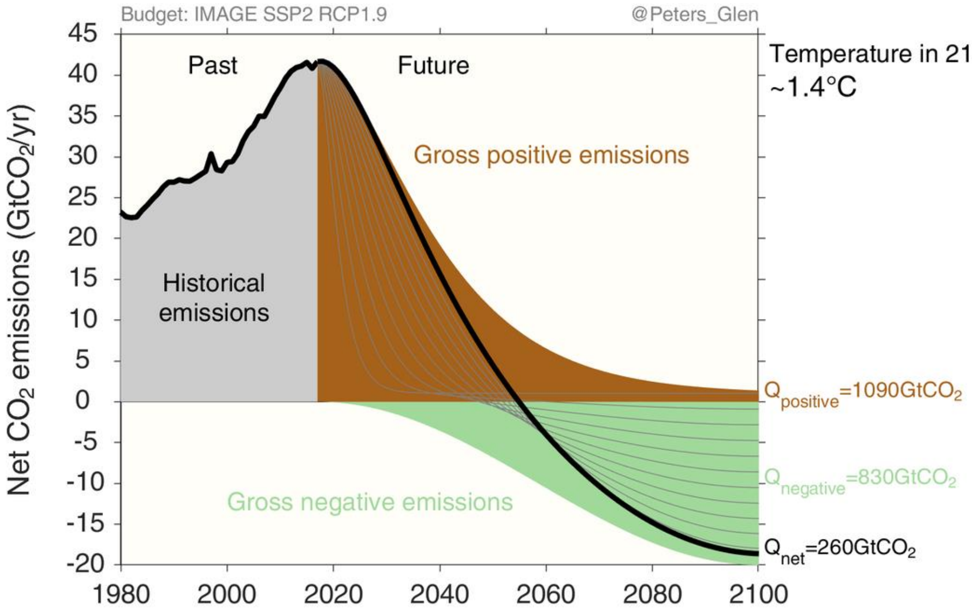

Figure 2. CO_2 reduction pathways with different levels of CDR.[6]

Taking into consideration natural warming, on a global average, the planet has already been warmed roughly 1°C by humans compared to the pre-industrial average[7], and temperatures are currently rising at a rate of 0.17°C per decade[8]. Air temperatures in Switzerland have already increased by about 1.5°C, (reaching 2°C in warmer years) during the last 150 years – more severely than the global average.[9] [10] [11] Globally nine of the ten warmest years on record have occurred in the 21st century. The rate of warming is expected to accelerate as greenhouse gases (GHG) keep on accumulating in the atmosphere. If the current commitments of the Paris Agreement were fully implemented by 2030, the world would be on a path to roughly 3°C of warming by 2100.[12]

The world currently addresses just a fraction of the emissions reductions necessary to achieve what is generally viewed to be sufficient risk mitigation, enshrined in the Paris Agreement's overarching objective. However, measures anticipated today within the countries' mitigation plans are limited to those options already in play. By contrast, most scenarios modelled in integrated assessment mod-

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[6] *G. Peters, 'Stylised pathways to «well below 2°C»', 2018.*

[7] *IPCC SR15, 2018.*

[8] *IPCC AR5, 2014.*

[9] *M. Begert and C. Frei, 'Long-term area-mean temperature series for Switzerland – Combining homogenized station data and high resolution grid data', International Journal of Climatology, vol. 38, no. 6, 2018, pp. 2792-2807.*

[10] *CH2018, 'CH2018 – Climate Scenarios for Switzerland, Technical Report', National Centre for Climate Services, Zurich, 2018, pp. 271.*

[11] *Bundesamt für Meteorologie und Klimatologie MeteoSchweiz, Temperatur- und Niederschlagsentwicklung,[website], 2019, www.meteoschweiz.admin.ch/home/klima/klimawandel-schweiz/temperatur-und-niederschlagsentwicklung.html.*

[12] *UNEP, 'The Emissions Gap Report 2018', 2018.*

els that achieve 2°C or even just 1.5°C rely on a much broader range of imaginable mitigation options[8] and far-reaching mitigation policies[13]. This implies that plans for mitigation must include substantial lifestyle changes across large populations (such as severely reduced global meat consumption), large-scale carbon capture and storage (CCS) from various hard to decarbonise point sources of CO_2, as well as CDR. All measures are necessary for the world to be heading in a direction in which 2°C would appear in reach with reasonable confidence.[14]

1.1 Key Insights on CDR from the Latest IPCC SR15 Report

The recently published IPCC special report on 1.5°C provided new insights on the impact of 1.5°C versus 2°C of global warming[15]. New evidence explicitly emphasises – more clearly than in previous reports – the difference one-half of a degree of additional warming can have on the livelihood of humans, animals, and oceans. The report concluded that limiting warming to 1.5°C is far more desirable than 2°C for the planet and the economy. Figure 3 summarises these differences.

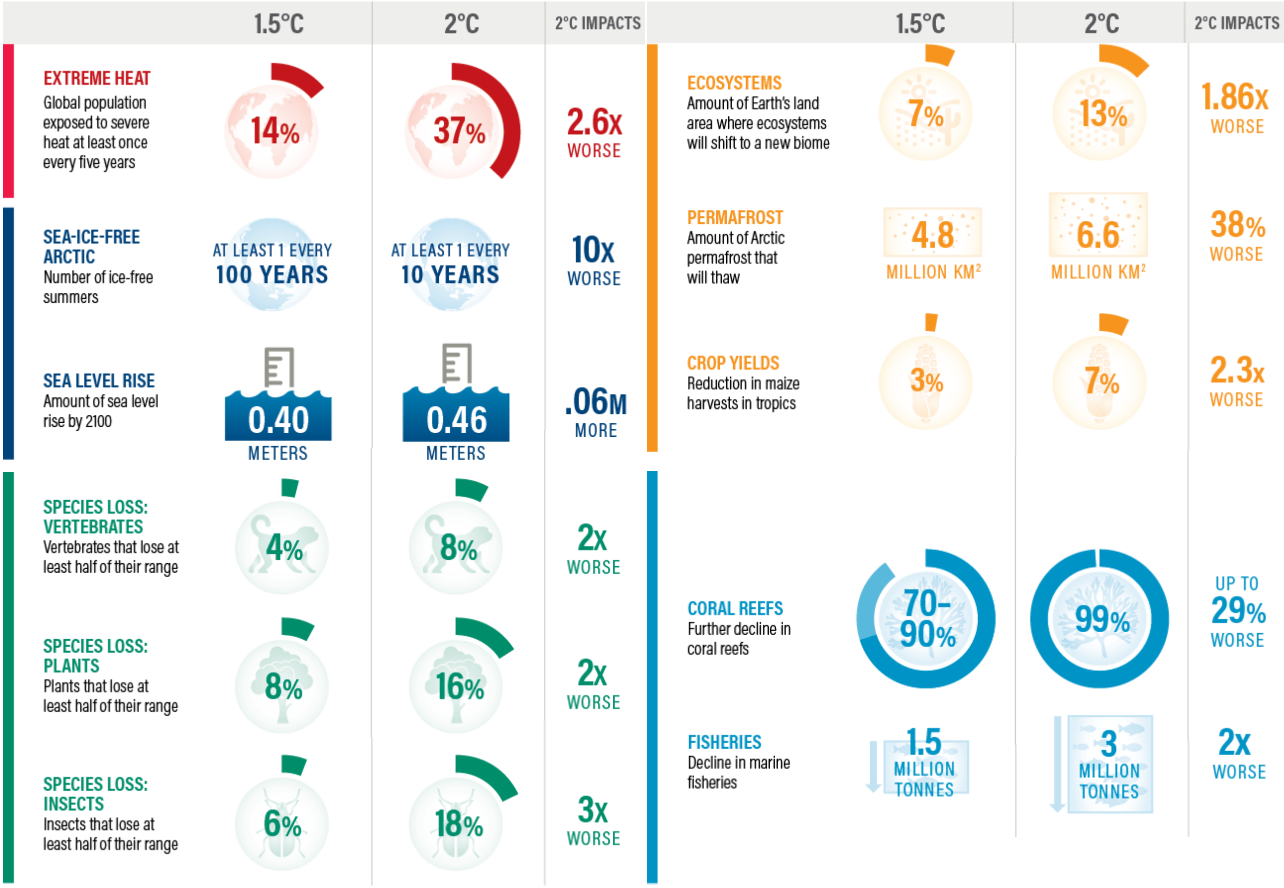

Figure 3. Impacts of 1.5°C vs. 2°C warming.[16]

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[13] *A. Michaelowa, M. Allen, and F. Sha, 'Policy instruments for limiting global temperature rise to 1.5° C – can humanity rise to the challenge?', 2018, pp. 275-286.*

[14] *The IPCC (2014) scenario that best corresponds to a 2°C world is called the Representative Concentration Pathway 2.6 (RCP 2.6). At the time of writing the last IPCC Assessment Report, there were not enough studies on pathways to 1.5°C available for serious consideration of such ambitious mitigation efforts.*

[15] *IPCC SR15, 2018*

[16] *World Resource Institute, 'Half a Degree of Warming makes a big Difference: Explaining IPCC's 1.5°C Special Report', 2018.*

The IPCC SR15 also prominently discussed the need for large atmospheric CO_2 removal for the first time. In terms of CDR, the report envisaged a range of 100-1000 billion tonnes of CO_2 (equaling 2.5 to 25 times the amount of current global annual emissions) that must be addressed by CDR within this century in order to achieve the 1.5°C warming target. The longer the world delays action on significant emissions reductions, the bigger the need for negative emissions.

In addition, the IPCC SR15 emphasises the following key learnings:

- All IPCC SR15 scenarios without overshoot already contain the assumption of a successful large-scale application of CDR, in addition to full mitigation efforts. In other words, according to the IPCC the successful development and deployment of CDR technologies is essential for reaching the 1.5°C target.
- Overshoot is essentially a byword for not sticking to the 1.5°C target, with all the negative implications for ecosystems and economy. This also means any additional CO_2 emissions will have to be removed later in the century in any case if the “overshoot” is to be mitigated.
- There is currently a disconnection between actual climate policy and the envisaged scales of deployment of negative emissions solutions needed which requires urgent attention.
- Only a clear commitment to a portfolio approach of different mitigation and CDR options, underpinned by strict adherence to policies, can lead to carbon neutrality by 2050.
- “Net zero emissions” means that any residual emissions explicitly, are a “Paris-compatible” option if they are not only compensated but reversed by appropriate deployment of CDR technologies.
- After net zero emissions have been achieved, only a further scale-up of CDR of several Gt leads to the requisite 1.5°C-compatible net-negative emissions in the second half of the century.

Still, in December 2018 at the UN COP24, leaders from around the globe, notably Saudi Arabia, USA, Kuwait and Russia, were not willing to “welcome" the IPCC's special report on limiting global warming to 1.5°C as a “UN welcome” would have implied endorsement and subsequently major political implications. In addition, the remaining carbon budgets have been a source of recent debate in climate science. Some stakeholders state that under the IPCC AR5 budgeting, the carbon budget for the 1.5°C target is already practically exhausted.

What does this mean for Switzerland? Burden sharing; demand for CO_2 emission reduction units will become highly competitive and prices of conventional mitigation should rise accordingly. Switzerland’s thought leadership and ability to translate ambitions into action are essential; Switzerland will be disproportionately hit by climate change as is already evident (see: CH2018 – Climate Scenarios for Switzerland[17]). Design and implementation of (Swiss) climate policy for the period post 2020 and especially post 2030 with regard to the challenges of implementing measures to reach domestic goals will thus become increasingly difficult. Therefore, Switzerland must develop legal and regulatory frameworks to enable research and innovation, pilot and demonstration projects to gather evidence now to be able to develop effective, cost-efficient and evidence-based mitigation and CDR policy instruments for the time after 2020 and 2030 respectively (for recommendation please see chapter 3)

1.2 Extreme Changes in Lifestyle as Only Alternative to Limit CDR

A recently published paper[18] concludes that meeting the 1.5°C goal is still possible without CDR deployment, but it requires massive changes in lifestyle. Mostly in diet (minimizing meat consumption

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[17] *CH2018, 'CH2018 – Climate Scenarios for Switzerland, Technical Report', National Centre for Climate Services, Zurich, 2018, pp. 271.*

[18] *A. Grubler, C. Wilson, N. Bento, B. Boza-Kiss, V. Krey, D. McCollum, N. D. Rao, K. Riahi, J. Ro-gelj,S. DeStercke, J. Cullen, S. Frank, O. Fricko, F. Guo, M. Gidden, P. Havlík, D. Huppmann, G. Kiesewetter, P. Rafaj, W. Schoepp, and H.*

as much as possible), mobility (-60% energy requirements, via car sharing and less cars on the road), or housing (-75% energy requirements) until 2050. In the absence of such drastic and world-wide changes, achieving net zero CO_2 in all industrial sectors is only possible with atmospheric CO_2 capture technologies in combination with ambitious mitigation,as CDR allows for compensation of unavoidable emissions from sectors such as building materials, aviation, heavy transport, agriculture and industry relying on carbon as a feedstock for products, such as large parts of the chemical industry. In these scenarios, CDR technology may also provide sustainable carbon from the atmosphere as a feedstock or raw material, helping to create carbon neutral synthetic fuels (unlike with CO_2 captured from fossil point sources) or even feedstock for carbon negative products, such as synthetic cement or building materials.

In light of today's global governance structures and today's limited effectiveness to embark on pathways to limit global warming according to the 2015 Paris Agreement, many stakeholders expect emissions to continue to rise, and thus an overshoot from given sectors (such as aviation) as highly likely. These sectors remain fundamental to the functioning of most societies and are therefore not only essential for people living in developed countries but as well for people in the developing world who strive for similar levels of material wealth and prosperity. Furthermore, net zero strategies for example presented by the aviation sector rely largely on the successful deployment of CDR technologies[19]. Therefore, the challenge for climate policy is twofold: To decouple emissions reductions from economic performance and to quickly achieve falling GHG emission pathways.

1.3 Moral Hazard

In context of mitigation and CDR the question of moral hazard is often raised. There are two forms of moral hazard[20]. Attributed to Anderson and Peters (2018), there is the risk of an inclusion of CDR technologies in climate models, which inform policy makers *without* making it explicit that additional policy measures are needed to develop them at sufficient scales, or to make explicit the risks needed puts current and future generations at great risk. Another form of moral hazard, often discussed by scientists and stakeholders is that politics might use the existence of CDR approaches to justify delays in mitigation efforts. In all considerations of CDR, it is important to keep this in mind.

1.4 More Ambitious Mitigation is Needed to Reduce Reliance on CDR

Today's climate policies and pathways to reduce emissions in most countries – including Switzerland – are insufficient to achieve the climate targets of the Paris Agreement. In other words, implicitly most countries that have signed the Paris Agreement already rely heavily on large-scale deployment of CDR to be deployed later this century.

Recognizing this implicit assumption, the majority of Swiss stakeholders emphasise the importance of steeper mitigation pathways, or pathways that are as steep as "reasonably practicable" to be assigned top priority to pro-actively limit the consequences of delayed mitigation, stronger-than-required reliance on CDRt scale during the second half of the century. In particular, Switzerland needs to pursue emissions reduction pathways that aim to achieve net zero GHG emissions by 2050.

Valin, 'A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies', Nature Energy, vol. 3, no. 6, 2018, p. 515.

[19] *European Federation for Transport and Environment, 'Roadmap to decarbonizing European aviation', 2018, www.transportenvironment.org/sites/te/files/publications/2018_10_Aviation_decarbonisation_paper_final.pdf.*

[20] *K. Anderson and G. Peters, 'The trouble with negative emissions: Reliance on negative-emission concepts locks in humankind's carbon addiction', Science, vol. 354, no. 6309, 2016, p.182-183.*

2 Carbon Dioxide Removal – CDR

CDR, synonymously referred to as negative emissions (NETs), consists of a range of (technological) approaches. As described in this chapter, some CDR approaches are ready for wide-scale deployment and market diffusion while others are at pilot and demonstration scales, and yet others are at a research and development stage. The portfolio of CDR approach options covers all approaches and commercial readiness levels. Naturally, they vary in cost, resource or energy needs, and ultimately in terms of actually realizable, technical and commercial CO_2 removal potential.

2.1 Overview of CDR Approaches in Switzerland

There is a wide range of CDR approaches that are currently proposed in the scientific literature, being researched & developed, tested or commercially applied. All at different technological readiness levels (TRLs).[21] Switzerland has stakeholders active in afforestration and forrest management, biochar, direct air capture (and storage), improved soil and agricultural management. Consequently, this report therefore will focus on these approaches, which are incidentally also amongst those frequently discussed in the relevant literature (Figure 4). The majority of information and material of each approach has been contributed by respective active Swiss stakeholders present in this project. Risk Dialogue Foundation therefore recommends that comprehensive life cycle analyses (LCAs) need to be considered to confirm the scope of the expected impact of individual CDR approach packages.

[21] This report uses the TRL classification 1 (Observation and description of the functional principle (8-15 years) to TRL 9 (Qualified system with proof of successful operation) https://de.wikipedia.org/wiki/Technology_Readiness_Level

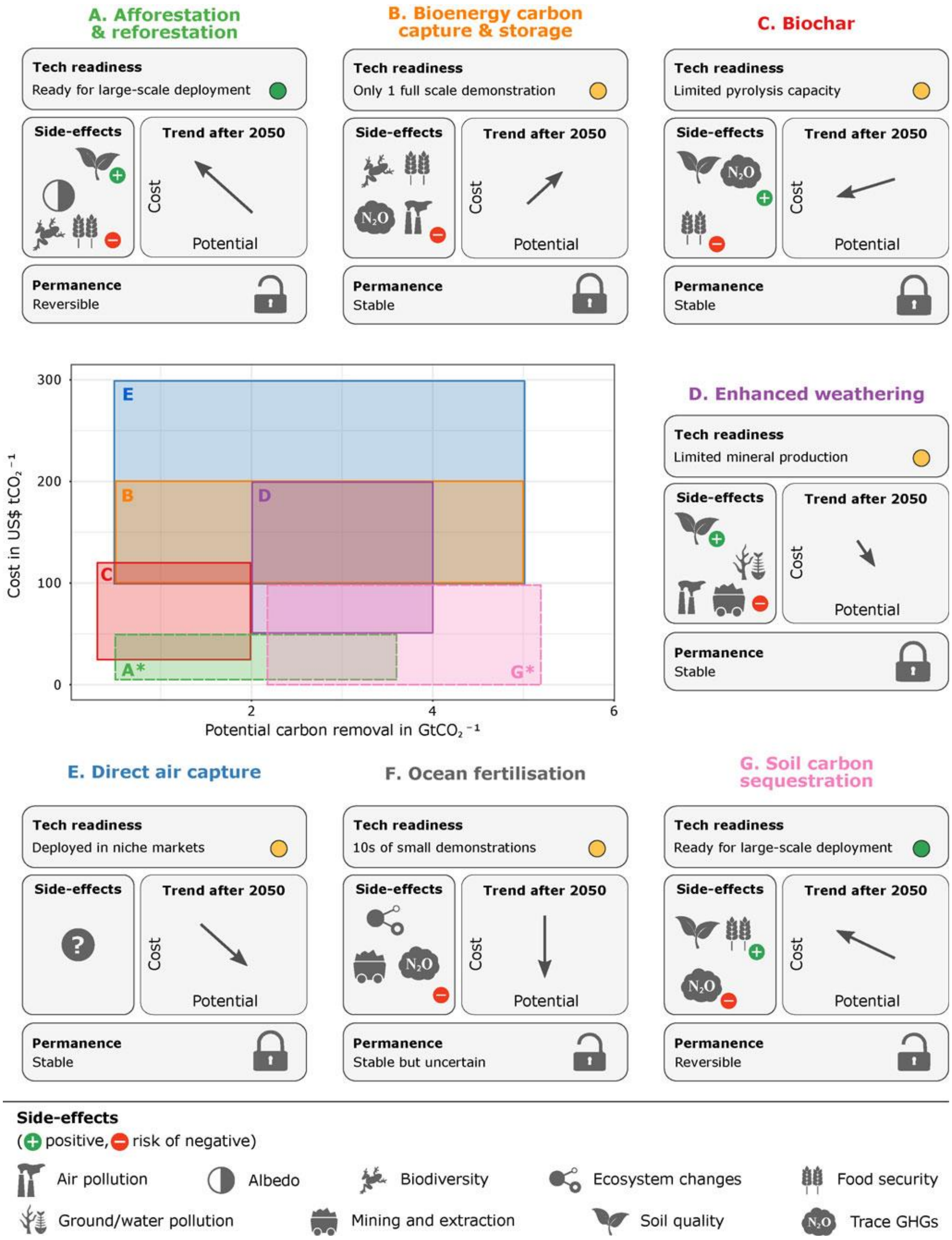

Figure 4. TRLs, Potentials, Opportunities and Risks of the most Prevalent CDR Approaches.[22]

CDR approaches like e.g. ocean based approaches are not included in the report. This because in order to provide a meaningful assessment there was insufficient knowledge among those Swiss based stakeholders Risk Dialogue Foundation was able to win for this project. This, however, does not mean that other approaches including ocean-based ones hold no future promise for Switzerland in general, or that they will not become relevant for Switzerland's future Nationally Determined Contributions (NDCs) to be achieved abroad and in accordance with Article 6 of the Paris Agreement

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[22] *J. C. Minx, et al., 'Negative emissions – Part 1: Research landscape and synthesis', Environmental Research Letters, vol. 13, no. 6, 2018, p. 063001.*

(see chapter 3.3.) once the Paris rulebook is finalised. A main factor for the feasibility of CDR approaches is cost. See Table 5 for current cost ranges of the subsequently discussed approaches (today and predicted floor costs) from the Swiss Academy of Sciences (SCNAT). It is important to note that these predictions include large uncertainties due to the early stages of some of the approaches. In addition, it is most important to note that especially approaches depending on biomass are subject to resource scarcity. Meaning that they could become more expensive if deployed at large scale.

CDR Group	Approach	Cost per tonne of CO_2 removed from atmosphere
CDR via biomass	Afforestation and forest management	1-100 CHF
	Improved soil and agricultural management	0-80 CHF
	Biochar (Pyrogenic Carbon Capture and Storage and Use: PyCCS+U)	10-135 CHF
	BECCS	50-250 CHF
CDR via technological approaches	DACS	40-1000 CHF
CDR via enhanced weathering	Enhanced weathering (via enhanced uptake in cement)	20- >1000 CHF

Table 5. CDR approaches can be grouped into three main approaches.[23]

2.2 CCS vs. CDR – Terminology and Definitions

In climate change discourse, CCS technologies are often viewed exclusively as a mitigation technology package, which is only deployed with fossil fuels. In general, fossil-fuel derived CO_2, captured at point sources from flue gas abates associated GHG emissions. Such applications (for example power generation from fossil fuels coupled with CCS) do not produce negative emissions and hence are not considered in this report. With the bulk of the world relying to 79% on fossil fuels to meet energy demand[24], CCS on fossils is a must in any given scenario for mitigation and hence according to some stakeholders also for Switzerland’s mitigation portfolio (77% of Switzerland’s 2017 energy demand comes from fossil fuels compared to 85% 20 years ago).

[23] *Akademien der Wissenschaften Schweiz, 'Emissionen rückgängig machen oder die Sonneneinstrahlung beeinflussen: Ist «Geoengineering» sinnvoll, überhaupt machbar und, wenn ja, zu welchem Preis?' Swiss Academies Factsheets, vol. 13, no. 4, 2018.*

[24] *IEA, 'Global Energy & CO_2 Status Report: The latest trends in energy and emissions in 2018', 2019, www.iea.org/geco/data.*

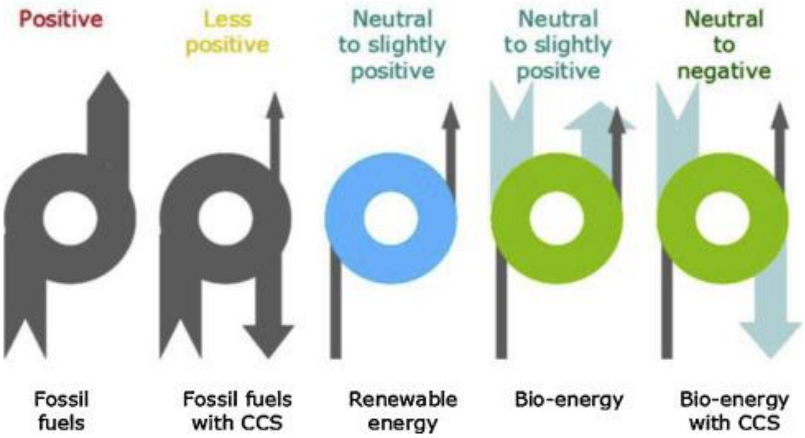

Figure 6. The difference between CCS and BECCS (or DACS).[25]

However, CCS technologies have a much wider scope for application and deployment (see Figure 6); abatement of CO_2 is essential to achieve CO_2 reduction targets for the industry and transport sectors; in one way or other CO_2 will need to be captured and subsequently stored. CCS may be deployed in Switzerland's cement sector in conjunction with other measures (such as biomass for coal substitution and energy efficiency) or in the paper & pulp production sector, thus at least theoretically leading to negative emissions, but this needs to be verified ideally via demonstration projects. It may furthermore be deployed in waste incineration plants, where biomass is burned together with other waste. If waste gas is captured during the burning this might – depending on the amount of biomass that is burned in relation to other (fossil) waste – lead to negative emissions, as this is essentially BECCS (see chapter 2.7). Also DAC is not a flue gas technology. This is why this report unlike many other refers to direct air capture and storage as DACS and not DACCS.

CCS technologies are thus part of some CDR technologies and should not be viewed as CO_2 abatement solution for fossil fuels only. Any narrative must pay careful attention to this fact.

[25] *J. Kemper, 'Biomass and carbon capture and storage – a review', International Journal of Greenhouse Gas Control, vol. 40, 2015, p. 401-430.*

2.3 Afforestation, Forest Management and Timber Industry

Improved forest management and wood use offer great CDR potential according to scientific consensus and many stakeholders. Though the potential of CDR related to planted afforestation is believed to be small in Switzerland by most stakeholders. Still, land abandonment and subsequent natural reforestation in mountainous regions may offer a large potential.

2.3.1 Approach

Afforestation is defined as a conversion to forest by active measures such as planting. Since 1990 CO_2 uptake by afforestation in Switzerland has been small (about 20 kt CO_2 eq. per year) and outweighed by deforestation (about -150 kt CO_2 eq. per year).[26] The afforestation area is very small (about 0.05 kha[27] per year compared to forest management area of 1'250 kha) and consequently, CDR potential is very small. In contrast, the potential to store CO_2 through natural reforestation is about 730 kt CO_2 per year assuming a biomass increment of 4.4 t per hectare per year (and thus 8t of CO_2 stored per hectare per year[28]) for 20 years and an expansion of the forested area by 4500 ha per year[29]. However, abandoned areas are decreasing.

The CDR potential of forest management is significantly larger. During the last three decades, the Swiss forest sink provided between 1.6 million t CO_2 eq. per year (2014) and 4.6 million t CO_2 eq. per year (1995) in CO_2 storage, with the exception of year 2000 when the forest constituted a source of 4.2 million t CO_2 eq. per year after the catastrophic storm "Lothar".[30]

Different management strategies can lead to very different short- and long-term effects.[31] In the long run, the CO_2 balance of Swiss forests may be optimised by utilising as much of the wood increment (newly added biomass) as possible, maximizing the production of long-lived wood products and finally, the utilisation of wood for energy generation in cascaded use. Implementing such a strategy, the CDR potential of the forest and wood industry is around 3 million t CO_2 eq. per year. Most of this is accounted for by energy and material substitution (1-2 million t CO_2 eq. per year), a smaller part is due to stock change of harvested wood products and the smallest part can be attributed to an increase of growing stock in the forest. Strategies that only increase the use of wood as biofuel are not efficient from a CO_2 balance perspective.31[31]

In contrast to the management strategy described above, reduced forest maintenance would allow to sequester large amounts of CO_2, at least initially. However, in the mid- to long-term this effect is reversed as decomposition starts to dominate and the system becomes a CO_2 source. Furthermore, such forests have a higher stability risk (exposure to be affected by windstorms, forest fires or insect outbreaks). A reduced maintenance scenario also competes with the wood use in the building and energy sector. In Switzerland forest corporations have recently started to modify their management to strengthen the sink function of forests and sell CO_2 certificates on the National voluntary market.

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[26] FOEN, 'Switzerland's National Inventory Report: GHG Inventory 1990-2017', 2019.

[27] 1 hectare = 0.01 km^2; 1000 hectares = 1 kha = 10 km^2

[28] E. Thürig and B. Traub, 'Non-forest areas converted to forest: standing stock, gains and losses in biomass', Report commissioned by the Swiss Federal Office for the Environment, Bern, 2015

[29] U.-B. Brändli, (Red.), 'Schweizerisches Landesforstinventar. Ergebnisse der dritten Erhebung 2004–2006', Swiss Federal Institute for Forest, Snow and Landscape Research WSL and Federal Office for the Environment FOEN, 2010, p. 312.

[30] These numbers were adapted to the new National Inventory Report (Table E-7), see: FOEN, 'Switzerland's National Inventory Report: GHG Inventory 1990-2017', 2019.

[31] F. Werner, R. Taverna, P. Hofer, E. Thürig, and E. Kaufmann, E., National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. Environmental Science & Policy, vol. 13, no. 1, 2010, p. 72-85.

2.3.2 State of Development

Forest management strategies are seen as ready for implementation as expressed by the expert stakeholders consulted.

2.3.3 Opportunities

As described in chapter 2.3.2 part of an ideal forest management strategy would be to replace energy intensive products manufactured in Switzerland by domestic, long-lived wood products such as building ceilings/floors or external walls. At the same time as wood products act as CO_2 sinks, they also support mitigation, due to lower energy intensity of production. After the service life of wood products, they can be combusted to replace fossil fuels (cascade use) and further support GHG mitigation.

2.3.4 Risks

The largest risk of afforestation and forest management are forests that reverse to become CO_2 sources and their exposure to large-scale natural damage (e.g. wind storms, forest fires, insect outbreaks, drought effects). As illustrated by the numbers in chapter 2.3.1, the forest was a large CO_2 source in the year after storm “Lothar” hit Switzerland. If the forest area were to be extended significantly (afforestation) this may lead to competition with food production and grazing land.

Natural reforestation changes the albedo radiative forcing as open land reflects more short-wave radiation than forest area. This leads to a decrease of the mitigation potential of reforestation in mountainous areas. [32]

Wood-fired heating systems can emit significant amounts of fine particles, which is best managed by imposing limits and deploying appropriate technology to clean flue gas.

2.3.5 Technological Readiness, Barriers and Open Questions

The approaches described are ready to be implemented. Challenges remain in monitoring.

[32] *J. Schwaab, M. Bavay, E. Davin, F. Hagedorn, F. Hüsler, M. Lehning, M. Schneebeli, E. Thürig, and P. Bebi, 'Carbon storage versus albedo change: radiative forcing of forest expansion in tem-perate mountainous regions of Switzerland' Biogeosciences, vol. 12, no. 2, 2015, p. 467-487.*

2.4 Improved Soil and Agricultural Management

Soil carbon sequestration (SCS) is a natural CDR technology, defined as a change in land management that leads to an increase in soil carbon (C) content and therefore a net uptake of CO_2 from the atmosphere. In contrast to afforestation or BECCS, SCS has the advantage that it does not compete with food production. Soil holds about twice the amount of C as the atmosphere. Some of the C has been historically released to the atmosphere and there is risk for further losses, for example through fires or drying peatlands. Additionally, in mineral soils large quantities of C are at risk when land is not properly managed. Therefore, CDR approaches in this sector have to be developed with a complete system view in mind.

The potential of SCS in Switzerland that has already been tested, has been found to be not material in impact but uncertainties are high.[33] However, agricultural practices to enhance soil organic carbon have many environmental co-benefits (e.g. improved water infiltration, reduced erosion, increased biodiversity), and are not very costly. Furthermore, these practices are important to prevent potential SOC losses (i.e. CO_2 emissions from soils) and contribute to climate resilience. Given the "technology readiness" and the fact that every tonne of C counts, SCS is to be encouraged to be taken up by the farming sector.

2.4.1 Approach

The amount of C in the soil depends on several factors, but most importantly, it is a balance of C inputs (e.g. roots, manure, harvest residues) and losses (mainly through decomposition and respiration). Soil C sequestration can thus be achieved by increasing C inputs or by reducing losses. Many different practices exist [34] [35], but not all are suitable for each region or country. Potential strategies depend on a range of local factors such as the agricultural practice including crop rotations and fertilisation regimes, the soil type, or climatic conditions. The following approaches are to some extent already applied in Switzerland, but warrant intensification: 1) the use of cover crops, 2) leaving harvest residues on the field, 3) return of organic residues to the field via fertilisation (farmyard manure, slurry, compost), 4) planting deep rooting crops, 5) grass-clover leys in crop rotations, 6) agroforestry, and 7) diversified crop rotations.

During the past three decades agricultural, mineral topsoils in Switzerland have been roughly CO_2 neutral.[36] Permanent cropland (without land-use change) on mineral soil was a very small CO_2 sink of 25 kt CO_2 eq. per year (0.017 t C per hectare per year; about 400'000 ha) and permanent grassland lost about 150 kt CO_2 eq. per year (-0.045 t C per hectare per year; about 920'000 ha). However, the uncertainty of these model-based estimates is large. Additionally, the sign and the rate of SOC change varied from year to year (soils were CO_2 sinks and sources).

To reach the goal of the 4 per 1000 initiative (Minasny et al 2017) a sequestration rate of 0.2 t C per hectare per year on cropland and 0.25 t C per hectare per year on grassland would be necessary. Whether these levels can be reached in Switzerland is uncertain. Based on results of an optimistic

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[33] *S. G. Keel, T. Anken, L. Büchi, A. Chervet, A. Fliessbach, R. Flisch, O. Huguenin-Elie, P. Mäder, J. Mayer, S. Sinaj, W. Sturny, C. Wüst-Galley, U. Zihlmann and J. Leifeld, 'Loss of soil organic carbon in Swiss long-term agricultural experiments over a wide range of management practices', Agriculture, Ecosystems and Environment, in press.*

[34] *P. Smith, D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko, M. Howden, T. McAllister, G. Pan, V. Romanenkov, U. Schneider, S. Towprayoon, M. Wattenbach, and J. Smith, 'Greenhouse gas mitigation in agriculture'. Philosophical Transactions of the Royal Society B: Biological Sciences, vol. 363, no. 1492, 2008, p. 789-813.*

[35] *R. Lal, 'Sequestering carbon in soils of agro-ecosystems', Food Policy, vol. 36, 2011, p.33-39.*

[36] *FOEN, 'Switzerland's National Inventory Report: GHG Inventory 1990-2017', 2019. Recalculated data (see 2020 submission of the GHG inventory for a rationale).*

French study, that partly included uncommon practices[37] 0.63 t C per hectare per year could be stored on cropland. For the entire cropland area in Switzerland applying this same rate would result in a C sink of 925 kt CO_2 eq. per year. It is important to note though, that C stocks will equilibrate and SCS is temporally limited. Assuming that C can be sequestered for the next 20 years at the rate documented for France on a constant area of about 400'000 ha, this may result in a potential of a cumulative sum of 18.5 million t CO_2. For permanent grassland, highest SCS rates for Swiss long-term experiments were 0.28 t C per hectare per year (based on linear regression across 12 years).[38] For 20 years and a constant area of 920'000 ha this results in a potential of a cumulative sum of 18.9 million t CO_2. These numbers represent maximum technical potentials in mineral topsoils using already established management practices.

Deep ploughing, a method used to improve soil structure, has been shown to increase soil organic carbon (SOC) stocks by significant amounts.[39] [40] Soil C sequestration resulting from this practice is the consequence of translocating large amounts of SOC that is not easily decomposable to greater depths, where soil carbon is largely protected from further decomposition. At the same time a new, undersaturated topsoil forms that can take up additional C. Compared to the practices described above, deep soiling is quite energy intensive (large tractor needed). However, the treatment is only applied once. Thus far, there are only few studies from Germany and New Zealand and thus the general applicability of this approach to farming and SCS has not been proven yet. Assuming this approach could be applied on 500 ha annually about 1.7 million t CO_2 may be sequestered in 20 years. If the ploughed area were to be increased to 5000 ha per year then about 15.4 milion t CO_2 could be stored over 20 years[41].

Reduced tillage (also referred to as no-till) has often been cited as a CDR approach. However, studies show an increase in soil C usually only in the topsoil (0-20 or 0-30 cm depth). At lower depths soil C decreases and over the whole soil profile the net effects are around zero. [42] [43]

2.4.2 State of Development

All approaches listed above in chapter 2.4.1 have already been tested in the field, are thus ready to be implemented and – except deep ploughing – have already been implemented by Swiss farmers to some extent, albeit without scientific accompaniment or monitoring. However, stakeholders agree that monitoring poses challenges. Effects of deep ploughing on soil C have so far only been measured in three studies. The generality of its positive effect needs to be investigated further.

2.4.3 Opportunities

The agricultural practices that can be applied as CDR approaches have many co-benefits. They reduce environmental impacts of fertilisation (cover crops can prevent nitrate leaching and may reduce N_2O emissions), reduce pests (crop rotation), produce fodder (grass-clover ley), improve water

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[37] *B. Autret, B. Mary, C. Chenu, M. Balabane, C. Girardin, M. Bertrand, G. Grandeau, and N. Beaudoin, 'Alternative arable cropping systems: A key to increase soil organic carbon storage? Results from a 16 year field experiment', Agriculture Ecosystems & Environment, vol. 232, 2016, p. 150-164.*

[38] *S. G. Keel et al., 'Loss of soil organic carbon in Swiss long-term agricultural experiments over a wide range of management practices', Agriculture, Ecosystems and Environment, in press.*

[39] *V. Alcántara, A. Don, R. Well and R. Nieder, 'Deep ploughing increases agricultural soil organic matter stocks', Global Change Biology, vol. 22, no. 8, 2016, p. 2939-2956.*

[40] *M. Schiedung, C.S. Tregurtha, M. H. Beare, S.M. Thomas and A. Don, 'Deep soil flipping increases carbon stocks of New Zealand grasslands', Global Change Biology, 2019, p. 1-14.*

[41] *At a rate of 500 ha per year.*

[42] *J.M. Baker, T. E. Ochsner, R. T. Venterea, T. J. Griffis, 'Tillage and soil carbon sequestration - What do we really know?', Agriculture, Ecosystems & Environment, 2007, vol. 118, no. 1-4, p. 1-5.*

[43] *Z. Luo, E. Wang and O. J. Sun, 'Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments', Agriculture, Ecosystems & Environment, vol. 139, 2010, p. 224-231.*

infiltration (cover crops), and reduce the risk of erosion (cover crops) or drought (deep rooting crops). TheSwiss agricultural system is strongly controlled by policies, which could be expanded to include CDR measures.

It is important to note, that the mitigation potential of organic soils under agricultural use (intact or degraded peaty soils) is large, as they emit -9.52 t C per hectare per year. The costs to regenerate these soils would be high on a per area basis[44] and would be associated with a decrease in agricultural production. But on a per unit of CO_2 basis, this would be a rather cost-effective approach in the view of participating expert stakeholders.

To simulate the demand side one solution could be to design and implement a certified product standard (e.g. a “CO_2 Knospe”) that denotes a CO_2 neutral or negative product to the customer, similar to “Bio Knospe” in Switzerland. This could also help to sensitise Swiss consumers for the need to buy CO_2 neutral products.

2.4.4 Risks

The most important risk for many of the measures is that SCS is reversible, if practices are not maintained because soil C is continuously decomposed. It is important to note, that soil C stocks tend to equilibrate when inputs are enhanced and that, given very high inputs, may even saturate [45] [46] (i.e. more input does no longer lead to higher SOC stocks). This means that the amount of C that can be sequestered in soil has an upper limit. Based on a study for Bavaria, a region comparable to Switzerland in terms of climate and soil conditions, significant amounts could be sequestered (Wiesmeier et al. 2014, GCB). For France, croplands and grasslands could store an additional amount of 15 to 31% of C in the fine fraction of soil.[45] Furthermore, there are practices that increase emissions of other GHG (e.g. fertilisation typically leads to N_2O emissions of soils) and can therefore have a negative influence on the total GHG balance. In some cases (e.g. agroforestry) crop yields might be reduced and production costs might increase.

2.4.5 Technological Readiness, Barriers and Open Questions

With the exception of deep ploughing, the approaches described above, are ready to be implemented and are already partly used. Numbers on the possible size of improvement do not exist for Switzerland. The barriers to implementation are lack of knowledge and trust in new practices among farmers, the increased workload and potentially higher costs.[47] The decision tool to select different approaches that improve the humus balance was developed by Agroscope.[48] Since the humus and carbon balance of soils are closely linked, a similar approach could be developed for C enriching practices. What remains a very challenging aspect, however, is monitoring the success of these approaches. Generally, changes in soil organic carbon stocks are difficult to measure (partly due to large heterogeneities of SOC within single fields) and it can take several years until new practices have a measurable effect.

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[44] *P. Smith et al., 'Greenhouse gas mitigation in agriculture'. Philosophical Transactions of the Royal Society B: Biological Sciences, vol. 363, no. 1492, 2008, p. 789-813.*

[45] *S. Chen, D. Arrouays, D. A. Angers, M. P. Martin, and C. Walter, 'Soil carbon stocks under different land uses and the applicability of the soil carbon saturation concept', Soil and Tillage Research, vol. 188, 2019, p. 53-58.*

[46] *C. Chenu, D. A. Angers, P. Barré, D. Derrien, D. Arrouays and J. Balesdent, 'Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations', Soil and Tillage Research, vol. 188, 2019, p. 41-52.*

[47] *In the canton of Solothurn a project was launched where farmers receive subsidies for humus enriching practices.*

[48] *Agroscope Humus Balance see: www.humusbilanz.ch*

2.5 Biochar (Pyrogenic Carbon Capture and Storage PyCCS[49])

Biochar is biomass-based charcoal, from for example harvest residues, produced at high temperature (400 to 650°C) in the absence of oxygen. This pyrolysis process yields C rich, aromatic products. Due to its high stability in the soil, biochar is regarded as a potential CO_2 sink. Adding biochar to agricultural soils has many co-benefits. It can positively influence the cycling of nutrients and increase the water-storage capacity.

2.5.1 Approach

Pyrolysis separates C, minerals and metals from the hydrogen and oxygen content of biomass – forming a porous mineral-rich charcoal, as well as other products such as oils (tars) or gases (syngas) and heat. The directly generated heat from pyrolysis is insufficient to auto-thermally sustain the process. Together with the generated oils and gases, however, 60% of the total energy content of the biomass is released and may not only be used to heat the process but also to meet other energy demands.

If applied to the soil, the bulk of the C trapped in biochar might stay in the soil for centuries or millennia.[50] Biochar forms also naturally by vegetation fires. In soils, pyrolytic C can contribute 4 to over 16%[51] to SOC (Figure 7). The very fertile soils of the Ukraine or southern Russia are especially rich in biochar from natural grassland fires accumulated over a long time. Pyrolytic C is highly stable, longer durable compared to any other organic matter in soils. A meta study of University Zurich about the worldwide research on this topic comes not to a clear statement in years (ranging from 291 years up to “inert” which would mean “infinite time for decay”).[50]

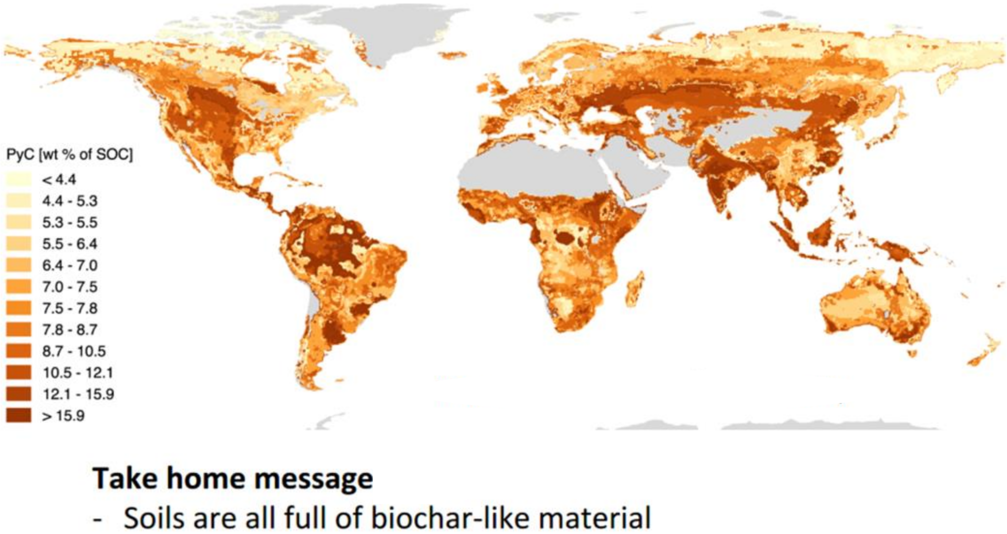

Figure 7. Soils naturally contain between less than 4.4% up to more than 16% of its carbon content in the form of pyrolytic carbon, biochar. The colours in Central Europe show 5.5 to 7.0% Pyrolytic Carbon content.[51]

[49] *H.P. Schmidt, 'Certification and trading of carbon sinks from biomass and biochar'; Ithaka Institute, Switzerland, 2019.*

[50] *S. Abiven, 'Overviews on fire-derived organic matter: stocks, persistence and impact on yields: Meta study of worldwide research', University Zurich; presented at the 1st round table on biochar at FOEN, 2016.*

[51] *M. Reisser, R. S. Purves, M. W. Schmidt and S. Abiven, 'Pyrogenic carbon in soils: a literature-based inventory and a global estimation of its content in soil organic carbon and stocks', Frontiers in Earth Science, vol. 4, no. 80, 2016.*

In this report, especially in Figure 9, a factor of 270 is applied as a conservative assumption by M. Schmid of Ökozentrum after reviewing literature on this.[52] [53] This factor states, that if the biomass growth and decay/composting or use as bioenergy cycle being "CO_2 neutral" is 100%, the PyCCS cycle slows this down by 270 times – so that a leakage of 1/270 = 0.37% of the carbon is returned into the atmosphere in the same time, when the biological decay of dead biomass would return 100% of the CO_2. As biomass can decompost and oxidize into CO_2 within one year or few years or two decades – the same could happen with biochar that can be oxidized within 270 years or 5'400 years with the figures of this assumption – or even in much longer periods, as we can find much older charcoal and coal on this planet.

The addition of biochar to soil improves nutrient retention.[54] The so called "Terra Preta" soils found in Brazil demonstrate the positive effects of biochar on the nutrient availability and the stability of pyrolytic C.[55] They occur on rare spots in wet tropical regions, where soils are usually poor oxisols and have been under agricultural use for 500 years without neither erosion nor loss of carbon content. These "man-made" soils have been formed by a mixture of compost, fire charcoals (pyrolytic carbon), faeces and existing soil 2'000 to 7'000 years ago.

Biochar can help retain water, potentially mitigating adverse effects of prolonged drought periods and heavy rainfall. If biochar is applied along an agricultural cascade of use, biochar can be economically and ecologically beneficial for farmers (Figure 8). This could mean, that the CDR effect (see below) would potentially be achievable at low or even negative net cost.

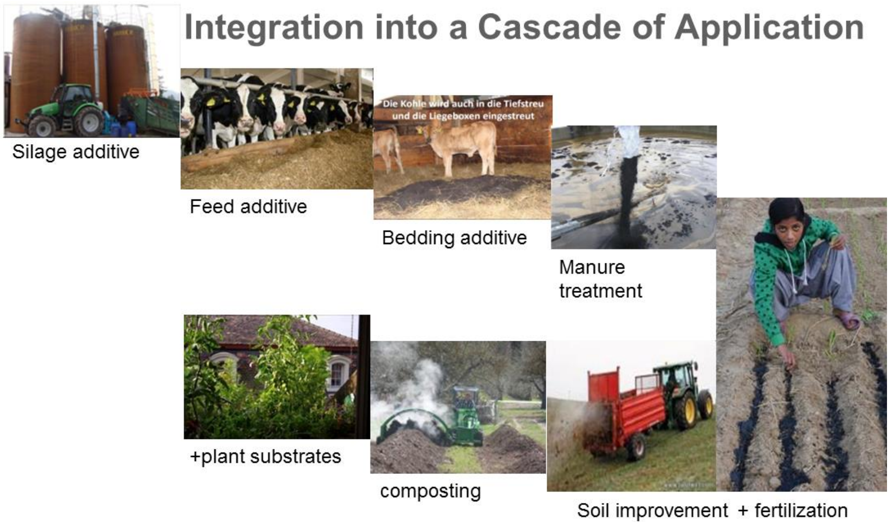

Figure 8. Integrating biochar in agriculture into a cascade of applications increases its economic and ecological benefits. While as silage additive, fungi are reduced, as feed additive methane emissions reduced and feed uptake increased, as bedding additive N_2O and NH_3 emissions and odors and claw infection are reduced, with manure treatment again N_2O and NH_3 emissions and odors, as well as fertiliser losses are reduced – and the same on the final destination grass- or cropland.[56]

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[52] *S. Abiven, 'Overviews on fire-derived organic matter: stocks, persistence and impact on yields: Meta study of worldwide research', University Zurich; presented at the 1st round table on biochar at FOEN, 2016.*

[53] *M. Reisser et al. 'Pyrogenic carbon in soils: a literature-based inventory and a global estimation of its content in soil organic carbon and stocks', Frontiers in Earth Science, vol. 4, no. 80, 2016.*

[54] *C. Kammann, L. Grünhage, D. Busch, C. Müller, G. Dörger, K. Hanewald and T. Schmid, 'Biokohle: Ein Weg zur dauerhaften Kohlenstoff-Sequestrierung', Hessisches Landesamt für Umwelt und Geologie, 2010, p. 1-8.*

[55] *B. Glaser, L. Haumaier, G. Guggenberger and W. Zech, 'The'Terra Preta'phenomenon: a model for sustainable agriculture in the humid tropics', Naturwissenschaften, vol. 88, no. 1, 2001, p. 37-41.*

[56] *Ithaka-Institute, 2018*

To visualise the CDR component of biochar, it is useful to follow CO_2 flows (expressed as % of the CO_2 stored by plant growth of the biomass, Figure 9).

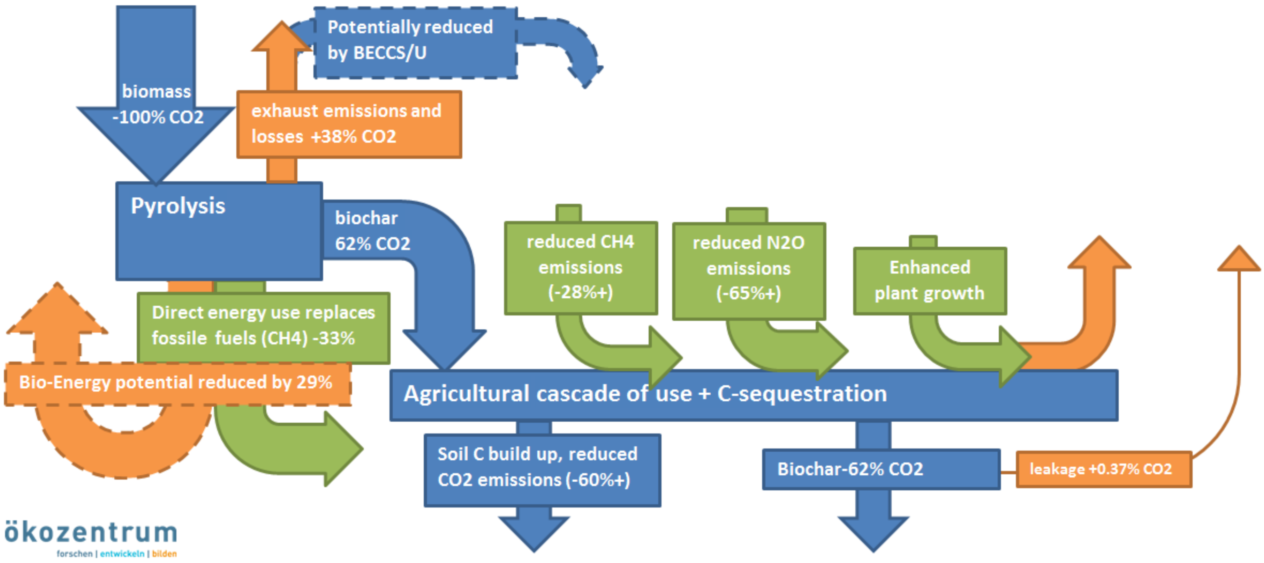

Figure 9. GHG-flows in the course of pyrolysis and the application of the biochar in agricultural processes and soil additive.[57] [58] [59]

The CDR effect is illustrated following the blue arrows in Figure 9. A potential additional GHG (not necessarily CO_2, but CH4 or N_2O) emission reduction effect becomes apparent when following the green arrows. Losses of GHG emissions back into atmosphere (unless captured and stored elsewhere) are shown by orange arrows Figure 9.

1) The biochar process flow shows that pyrolysis can stabilize and store as biochar 62% of the CO_2, which has been captured and used by the biomass plant growth.
2) The remaining 38% of the C content burns off during the process of pyrolysis. From the flue gas, the CO_2 could be captured and subsequently stored in geological reservoirs, thus having a biochar facility function as a BECCS facility (bioenergy plant equipped with CCS technology – see chapter 2.7).
3) Pyrolysis includes the exothermic combustion of syngas/oil and converted heat energy could replace fossil fuels (green arrows contributing to additional GHG emission reductions of up to 33%).
4) However this renewable-energy potential is reduced by the production and storage of the biochar itself (shown as a dashed orange arrow with 29%)
5) Once applied in agriculture, the presence of biochar induces additional effects which can be emission reduction (not CDR, green arrows) or again soil carbon build up (CDR, blue arrow). If the stated value is smaller than 62%, it means: the GHG-relevant effect is estimated to be smaller than the direct carbon offset of the biochar itself. If the value is higher than 62%, the GHG-relevant effect is estimated to be higher than the biochar CDR effect.

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[57] *H. Blaser and F. Abächerli, 'Verschiedene Erfahrungen in Gesprächen wiedergegeben', Langenbruck, Faoug, Neuheim, 2016/2017/2018.*

[58] *A. Gattinger and M. Scheifele, 'The returning N2O effect of biochar in soils', presented at FiBL, Frick, 2016.*

[59] *S. Schimmelpfennig, C. Müller, L. Grünhage, C. Koch and C. Kammann, 'Biochar, hydrochar and uncarbonized feedstock application to permanent grassland – Effects on greenhouse gas emissions and plant growth', Agriculture, Ecosystems & Environment, vol. 191, 2014, p. 39-52.*

6) The CDR effect of soil Carbon build-up could be up 1 to 5 times higher than the CDR effect of carbon storage of the PyCCS effect itself. In the above graph, the effect is estimated with factor 0.97 (60%).
7) Generally the CH_4 effects are referring to the biochar use as a bedding- and feeding- as well as a manure treatment additive – and as a minor effect also in the soil[60]
8) Generally the N_2O effects are estimated to be mainly in the soil as those can happen repeatedly over several years or decades[60] [61] but also in the barn (bedding)[62] and manure treatment.

To summarize, it can be said, that biochar and its production (pyrolysis) and application in agriculture can achieve a GHG relevance of more than 256% of the amount of CO_2 that has been captured by the plant (biomass) growth from the atmosphere. 160% of the mentioned >256% could be CDR. The "direct" CDR effect of the sequestered biochar itself is only 62%, as said.

2.5.2 State of Development

Production of biochar – Pyrolysis

The production of biochar is similar to the production of grill charcoal. Biochar can be generated in clean and energy efficient units, such as the PPV300 (produced by Le Viet Hien Mech. Co. Ltd. Vietnam) and the CPP800 (Figure 10; made in Switzerland by Compag, Kreuzlingen).

Technologies for clean biochar production as well as for application in the agriculture sector is currently being piloted in Switzerland (Ökozentrum Langenbruck, Agroscope, HAFL (BFH Zollikofen) and ZHAW). There is currently a wide range of research and development projects. EAWAG (tropical soils and human faeces and urine management); FiBL (agricultural benefits and yield improvement); Agroscope (GHG emissions from soils, development of standards for biochar (European Biochar Certificate EBC); Ithaka-Institute (development of agricultural ecosystems in Europe and Asia); HAFL (N efficiency of application of biochar as bedding material); and ZHAW Wädenswil (faeces management, nutrients recycling).

Pyrolysis technologies are currently being tested and applied in Switzerland by Verora, AgroCO2ncept and Ökozentrum and their partners. Research for CDR effects of biochar in soils is ongoing at Agroscope [63] [64] [65] [66] and in field testing and monitoring of Agroscope at the project AgroCO2ncept in Flaach ZH[67].

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[60] *S. Schimmelpfennig et al.,'Biochar, hydrochar and uncarbonized feed-stock application to permanent grassland – Effects on greenhouse gas emissions and plant growth', Agriculture, Eco-systems & Environment, vol. 191, 2014, p. 39-52.*

[61] *A. Gattinger and M. Scheifele, 'The returning N2O effect of biochar in soils', presented at FiBL, Frick, 2016.*

[62] *E. Seitler, 'Reduktion von NH_3-Emissionen aus Mist mittels Pflanzenkohle sowie Methodenentwick-lung für Ammoniakmessung im Stall', Master Thesis, FHNW, 2015.*

[63] *T. Keller, R. Hüppi and J. Leifeld, 'Relationship between greenhouse gas emissions and changes in soil gas diffusivity in a field experiment with biochar and lime', Journal of Plant Nutrition and Soil Science, vol. 182, no. 4, 2019, p. 667-675, (peer reviewed 2019).*

[64] *N. P. Buchkina, R. Hüppi and J. Leifeld, 'Biochar and short-term N2O and CO2 emission from plant residue-amended soil with different fertilisation history', Zemdirbyste-Agriculture, vol. 106, no. 2, 2019, p. 99-106, (peer reviewed 2019).*

[65] *R. Hüppi, R. Felber, M. Krauss, J. Six, J. Leifeld and R. Fuß, 'Restricting the nonlinearity parameter in soil greenhouse gas flux calculation for more reliable flux estimates', PloS one, vol. 13, no. 7, 2018, e0200876, (peer reviewed 2018).*

[66] *J. Leifeld, C. Alewell, C. Bader, J. P. Krüger, J. P., C. W. Mueller, M. Sommer, M. Steffens and S. Szidat, 'Pyrogenic carbon contributes substantially to carbon storage in intact and degraded northern peatlands', Land degradation & development, vol. 29, no. 7, 2018, p. 2082-2091, (peer reviewed, 2018).*

[67] *A. Meier et al., 'Projekt AgroCO2ncept, 26 Landwirtschaftsbetriebe wollen Klimapositiv werden', Flaach, 2016.*

Figure 10. COMPAG CPP800 unit for 2‘400 t/a wet or dry wood chips and wood screening residues. The unit produces 50 kW electric power with a hot air turbine and up to 350 kW heat for greenhouse heating. The expected biochar production is to 400 t/a. Picture taken during delivering of the first unit to a bigger organic farm with greenhouses in Region Zürich, January 2019.

Market

Biochar use in agriculture and soil management is a small, young, yet fast growing market in Switzerland. The use of biochar as feed additive amounted to 160 tonnes in 2018 and as a bedding additive, composting and manure treatment to be later used for soil enhancement to 1’400 tonnes in 2018.[68] The market is currently much smaller than that of using biochar as active char (to be later burned in waste incinerators) at 7’000 tonnes in 2018.[69] Similarly some 13’000 tonnes of charcoal have been used for “BBQ”.[70] In total, the consumption of biochar-like products in Switzerland was roughly 22’000 tonnes by 2018.

Legal situation

The use of biochar as a feed additive, for medical treatments, as water filter and air filter has always been permitted and is in use traditionally. However, as soil treatment it has only been permitted in Switzerland since March 2013 within the fertilizer regulation. Since 2018 EBC-certified biochar is listed as allowed soil additive for organic farming “BioSuisse” and “Demeter”. Conditions in Austria (since 10. 2018) and Italy (1. 2016) as well as in Sweden and Norway are similar. Just now (July 2019), biochar is included in the EU Fertilizers Regulation - adopted but not yet approved: The authorized substrate materials for the production of biochar will be regulated and added to the Regulation as Annex 2. This is expected to happen until the end of 2019.

[68] M. Schmid, 'Interviews of 6 biochar importers, producers and traders and 3 feeding additive producers and traders in Switzerland', Market analysis for customers in ZH and TG, Langenbruck, 2019, unpublished.
[69] H. Fichtl and M. Jutz, 'Abschätzungen und teilweise Erhebung, sowie Vergleich mit anderen Quellen von Daten zum Aktivkohle-Import in die Schweiz im Zuge der Einführung der Pflicht zur 4. Klärstufe bei ARA in der Schweiz', Zürich, 2019.
[70] eurostat 2017, as cited in WWF, 'Marktananlyse Holzkohle 2018: Wir grillieren den Tropenwald', 2018.

2.5.3 Opportunities

It is agreed among scientists[71], pilot farmers and the federal agency of agriculture that the annual biochar use in Switzerland – which creates enough beneficial side effects, so its application is in total free of costs or even at negative costs – is expected to be 0.5 tonnes per hectare and year. This as well for crop land and managed grasslands without alpine regions. Additionally, the entire peat imports for gardening substrates shall be replaced by using instead a mixture of biochar and compost. This would sum up to a total need of 600'000 t per year biochar for Swiss agriculture and gardening. As there is no upper limit of soil carbon content (Peat lands have up to several thousand tonnes of carbon per hectare), this could be practised as long as necessary and helpful. This would also enable the application of biochar in feeding and bedding based on the actual number of farming animals, with the mentioned co-benefits on health, odors and N-based GHG emissions.

Concerning the local national production, it can be said that only the sustainable additional biomass potential – not yet used but ecologically and economically useful potential – is at least 17.6 megatonnes (Mt) fresh substrate (2.8 Mt dry matter).[72] With a carbon retention efficiency of 62%, this corresponds to a potential of 0.9 Mt biochar which is higher than the mentioned maximum market volume of 600'000 t per year.

The "direct" CDR effect (carbon sequestration of the biochar only) of this 600'000 t per year biochar application and finally storage in soils is almost 2.2 Mt of CO_2 per year.[73]

The production of 600'000 t of biochar per year within Switzerland would also supply 4.4 TWh of renewable energy per year. Replacing fossil fuels like light fuel oil, this would reduce GHG emissions by additional 1.28 Mt CO_2 per year. The additional co-benefits and GHG emission reductions from agriculture and soil C build-up would add additional GHG emission reduction as mentioned.

In summary, the total "Terra Preta effect" if applied consistently, which is biochar plus its effects of soil carbon build-up and other GHG emission reductions, plus the clean energy of pyrolysis may theoretically sum up to roughly 9 Mt CO_2 eq. per year. This would correspond to ca. 18% of current Swiss emissions. Combining PyCCS with BECCS, the exhaust CO_2 emissions once captured and stored may allow the removal of another 0.8 Mt of CO_2 per year. If this is feasible in practice depends on available biomass however. According to Thees et al. (2017)[72], a sustainable potential of 2.8 Mt biomass (dry weight) is available yearly in Switzerland, that could alternatively/additionally be used for energy purposes or for storage (BECCS) (compared to today). The reduction of CO_2 in the air by converting and storing biomass, has therefore a theoretical potential itself of 5.1 million tonnes CO_2 per year.

Developing the full biochar potential requires ramping up the manufacture of pyrolysis plants between today and 2028 to a rate of 60 units per year and then steadily manufacturing and commissioning them until 2050 at that rate. Each of the units produces 400 t biochar per year as well as heat and power from renewable bio-energy sources. This rate of dissemination seems feasible. In more common figures, calculated in yearly %-growth rates, arriving at 600'000 t per year biochar production in 2050 is 11% growth from now on.

2.5.4 Risks

Most prominent barriers for the full-scale application of biochar include competition for use of available biomass in the energy sector and agricultural management (see chapter 0). However, biochar

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[71] O. Thees, V. Burg, M. Erni, G. Bowman und R. Lemm, 'Biomassenpotenziale der Schweiz für die energetische Nutzung', Ergebnisse des Schweizerischen Energiekompetenzzentrums SCCER BIOSWEET, WSL Bericht, no. 57, 2017, p. 299.

[72] O. Thees et al., 'Biomassenpotenziale der Schweiz für die energetische Nut-zung', Ergebnisse des Schweizerischen Energiekompetenzzentrums SCCER BIOSWEET, WSL Bericht, no. 57, 2017, p. 299.

[73] $CO_2 = 3.66 \times C$ (mol mass calculation) $600'000 \times 3.66 = 2.2 \times 10^6$

in combination with CCS (BECCS, see chapter 2.7) may provide an opportunity that offsets some of the competitive forces. Future BECCS plants could play a synergic role, as the CCS technologies could use the exhaust from pyrolysis plants. Participating stakeholders from the Swiss biochar community do not expect any competition for available land and water resources and with food production.

As with all technologies, there are operational risks. Biochar should never be applied to soils without soaked as it absorbs and stores nutrients, but instead after having been soaked with manure, urine, other liquid bio wastes, or water. Also, biochar may pose an increased fire hazard if dry biochar is applied to soil as dark colour increases the conversion of sunlight to infrared heat. However, the effect of biochar in soil is expected to increase the water holding capacity and fertility, which reverse the fire hazard risk. The risk of soil contamination is expected to be negligible provided biochar is produced in accordance with specifications such as the European Biochar Certificate (EBC).

2.5.5 Technological Readiness, Barriers and Open Questions

According to the Swiss biochar stakeholders present, the technology is ready to be used commercially (TRL 7-8) in Switzerland. Some business cases have already been established. Funding for deployment and market diffusion is still important. For small-scale farm holdings, the main barrier to apply biochar are the high costs.

Although soil analysis is done on every Swiss farm within every decade at least once, the monitoring the application of biochar in agriculture is not yet regulated, as also the carbon content of the soils is rather “estimated” than measured now. Of interest is an Austrian initiative related to certificates of origin, the “Humus-Zertifikate” of the Austrian Eco-region Kaindorf (A). Independent and regular testing of soil carbon contents is necessary on farmland when biochar is applied in the agricultural sector. At the international level, biochar has been acknowledged to be a very strong and likely feasible CDR measure by the IPCC in October 2018.[74] However, biochar is still not accepted for carbon offset projects as charcoal is also considered a fuel.

[74] *Ithaka Institute, 2018*

2.6 Direct Air Capture (DAC)

2.6.1 Approach

Carbon dioxide can be removed from ambient air through chemical and engineering processes and subsequently stored. Traditional modes of carbon capture, such as pre-combustion and post-combustion CO_2 (CCS) capture from large point sources, can help slow the rate of increase of the atmospheric CO_2 concentration, but only the direct removal of CO_2 from the air, or “direct air capture” (DAC), can actually reduce the global atmospheric CO_2 concentration when combined with long-term storage of CO_2.

2.6.2 State of Development

One of three well-known DAC companies in the world, besides Global Thermostat (USA) and Carbon Engineering (Canada), is Climeworks, based in the Canton of Zürich. As the project worked with Swiss stakeholder only, this meant that only stakeholders from Swiss based organisations where present. The chapter therefore focuses on Climeworks’ DAC technology. Climeworks to date has 16 plants in operation throughout Europe. Their history and development illustrate the role Switzerland-based original equipment developers and manufacturers may have in a future global market for CDR technologies; Climeworks was established as an ETHZ spin-off in 2009, and now (April 2019) has a highly specialised (75+ FTE as of August 2019) workforce actively developing DAC technology and selling it in the market place. Building on operational experience, Climeworks maps out a path towards commerciality for its DAC plants. Operational DAC plants provide valuable insights for the development of three different applications, all of which have the potential to be considered CDR technologies.

The most relevant is the combination of DAC with geological storage, leading to, for example, long-term storage of CO_2 in a mineralised state. Climeworks has designed its technology amine adsorbents require only approximately 85–120 °C to desorb the captured CO_2 from the filter, meaning that waste heat can be used and in a modular way, allowing fast innovation cycles and efficiency gains in mass-production. USA-based Global Thermostat follows a similar approach. Canadian Carbon Engineering approaches DAC via hydroxide solutions that require high-temperature heat ($T > 800$ °C) to relase the captures CO_2, which can be provided by burning natural gas, which in turn requires that the released fossil CO_2 from burning gas is co captured[75]. Canadian Carbon Engineering however in theory has comparative advantages in single plant efficiencies operating at large scale.

[75] *G. Realmonte, L. Drouet, A. Gambhir, J. Glynn, A. Hawkes, A. C. Köberle and M. Tavoni, 'An inter-model assessment of the role of direct air capture in deep mitigation pathways', Nature communications, vol. 10, no. 1, 2019, p. 3277.*

Direct Air Capture in Switzerland: Commercial Launch

Figure 11. Climeworks' commercial DAC plant annually delivering about 900 tonnes of food-grade CO_2 as fertiliser to a greenhouse operated by Gebrüder Meier in the town of Hinwil (Canton of Zurich). A nearby waste-to-energy plant supplies the heat to regenerate the proprietary capture material.[76]

The world`s first commercial DAC plant, located outside Zurich, Switzerland, consists of 18 modules (known as "CO_2 collectors") and has a nominal capacity of 900 tonnes of atmospheric CO_2 per year. The plant was commissioned in May 2017 and delivers air-captured CO_2 to a greenhouse to increase crop yield. With this plant, Climeworks was the first company worldwide to capture atmospheric CO_2 and supply it to a customer.

With a view towards standardising and unitising modules, the DAC plant was built in compliance with required industry standards (e.g. EU Pressure Equipment Directive (PED), CE marking). By operating autonomously over two years and delivering a continuous stream of high purity CO_2 gas (> 99% purity), the plant meets its customer requirements, thus demonstrating its commercial viability. Three standard 40-foot shipping containers filled with six CO_2 collectors each are operated in sequence, so that batch processing guarantees continuous delivery of CO_2. Other commercial applications of this kind include supply of CO_2 to the beverage industry.

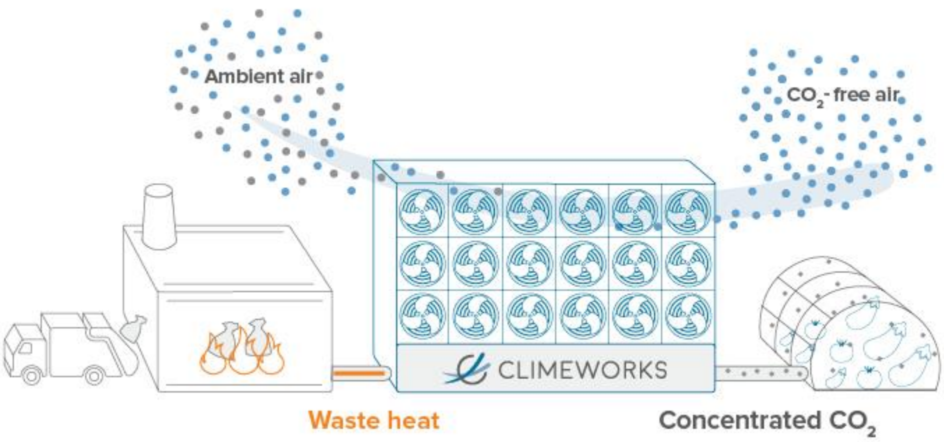

Figure 12. Atmospheric CO_2 Removal and use as fertilizer.[76]

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[76] *Climeworks, 2017.*

CDR via DACS

A negative emissions DAC plant is located in Iceland, where Climeworks commissioned the world's first Direct Air Capture and Carbon Storage (DACS) plant. The Hellisheidi geothermal power plant supplies electricity and waste heat for DAC operations. The DAC plant is part of the 'CarbFix2' project, financed by the European Union's (EU) Horizon 2020 program, as is the development of the storage process that is a breakthrough innovation in itself. The project, led by Reykjavik Energy, aims to develop an economically viable and complete atmospheric carbon capture and mineralisation chain.[77]

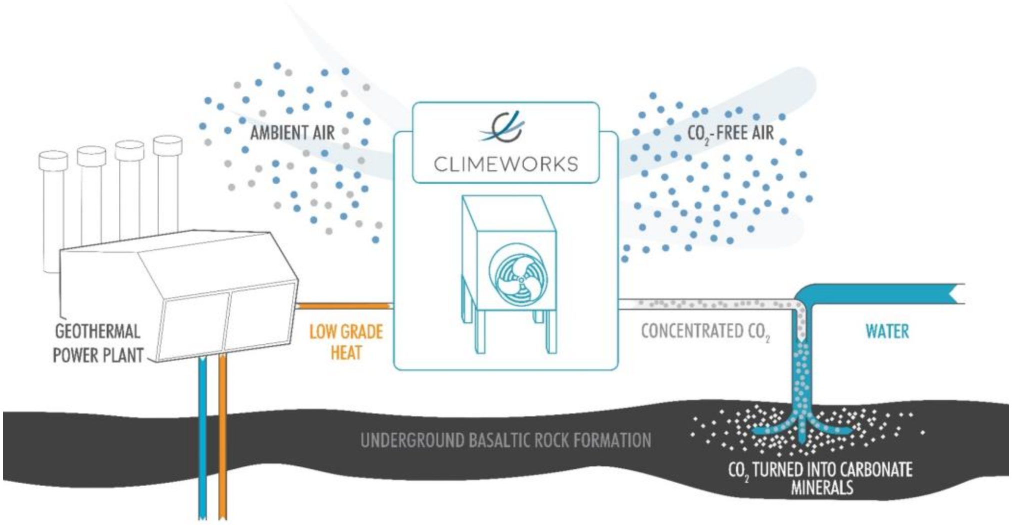

Figure 13. The world's first DACS project in Iceland, where ubiquitous basalt is the ideal rock to allow for fast mineralisation of CO_2 into a solid mineral. Thus, the mineral traps and removes CO_2 from the atmosphere.[78]

Until now, most other subsurface carbon storage projects have injected CO_2 into depleted oil and gas fields or saline aquifers. There, some of the supercritical CO_2 enters available pore space in rocks, some of the CO_2 dissolves in water and the remainder eventually mineralises. In contrast, CarbFix mineralises CO_2 into calcite at much higher rate owing to the presence of basaltic (magnesium and iron-rich) rock formations. This results in an even lower (near-zero) risk of leakage particularly suitable when there is no sealing cap rock present, since the CO_2 has been fixed in a solid phase/mineral.

Figure 14. Left: a bore core with mineralized atmospheric CO_2 from the world`s first DACS plant at the Hellisheidi geothermal powerplant (right).[77]

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[77] *CarbFix, 2019, www.carbfix.com, (accessed 10 July 2019).*

[78] *Climeworks, 2017.*

The DACS pilot builds upon the same system technology as the DAC plant in Hinwil ZH. Even under the harsh Icelandic environmental conditions (e.g. sulfur dioxide present in the CO_2 stream, extreme weather conditions and temperatures), the plant demonstrates its functionality. To conclude, the combination of DAC technology with geological storage was thoroughly tested, major technical issues have been overcome and it was thus successfully piloted.[79] [80] Besides choice locations such as Iceland, there are ample suitable basaltic storage sites for example in the Middle East, South Africa and the Northwest of the USA.

STORE&GO (Power to X)

Figure 15. DAC 3 plant as part of STORE&GO.[81]

Another DAC plant using CO_2 from ambient air for synthetic methanation was installed in Troja, Italy in July of 2018 as part of the Horizon2020 EU funded STORE&GO[82] project, and started operation in October of the same year. The DAC unit consists of three collectors using the latest Climeworks' technology and requires less energy than the DAC-18 plant in Hinwil, Switzerland. Making use of excess on-site photovoltaic power, an alkaline electrolyser (200 kilowatt) locally generates 240 cubic meters of renewable hydrogen per hour. The captured CO_2 and renewable hydrogen generated on-site are then catalytically methanated (Power-to-gas) in modular reactors provided by the French company ATMOSTAT. Waste heat retrieved from the reactors' cooling circuits is extracted for the operation of Climeworks' DAC-3 facility. The methane is then liquefied and used as a "clean" transportation fuel for heavy good vehicles (HGVs).

The primary objective of the STORE&GO project is to demonstrate the viability of large-volume energy storage through power-to-gas technology in a field setting. The EU plans to use 43% renewable energy by 2030 and 50% by 2050. In order to do so, the EU expects to require additional energy storage facilities. Making use of the Europe-wide natural gas network in conjunction with STORE&GO technology has considerable potential.

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[79] V. Gutknecht, S. Ó. Snæbjörnsdóttir, B. Sigfússon, E. S. Aradóttir and L. Charles, 'Creating a car-bon dioxide removal solution by combining rapid mineralization of CO_2 with direct air capture', Energy Procedia, vol. 146, 2018, p. 129-134.

[80] For scientific papers of CarbFix see: www.carbfix.com/scientific-papers

[81] Climeworks, 2018.

[82] STORE&GO project, see: www.storeandgo.info

As the emerging DAC industry demonstrates, integrating DAC technology into an energy system has major upsides such as providing energy storage, enabling the production of clean fuels or acting as a CDR technology.

2.6.3 Opportunities

In addition to the opportunities discussed above. While many other CDR technologies rely on very large industrial facilities, essentially chemical plants that are bolted on energy conversion and production facilities (e.g. power plants, cement, steel, paper and pulp), the flexibility of DAC plants may prove to be an outstanding opportunity to capture any sized market, including strongly decentralised efforts to capture CO_2 and offset other diffuse sources.

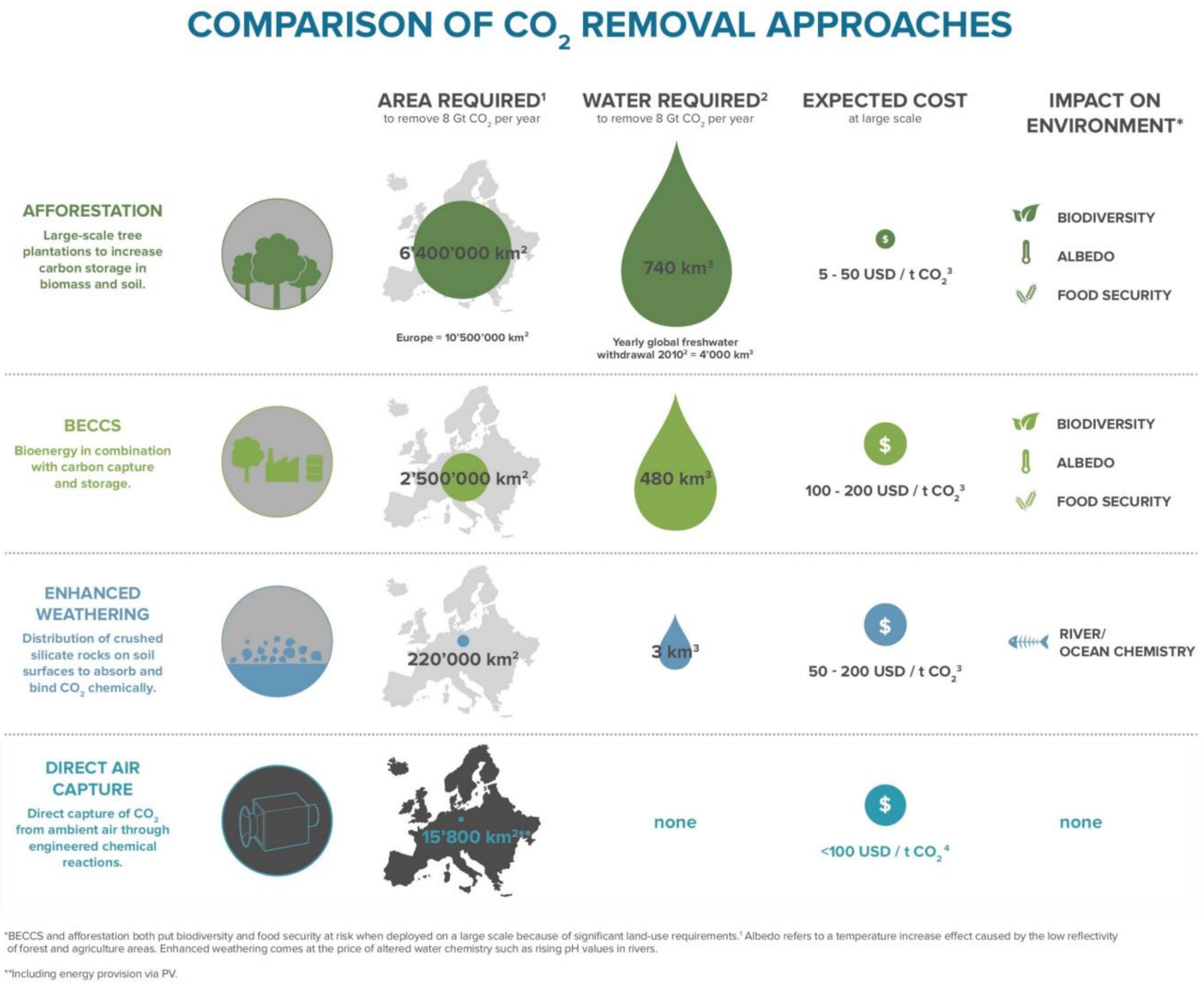

Figure 16. A comparison of CDR approaches.[83]

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[83] *Figure from Climeworks based on the following sources: P. Smith et al., 'Biophysical and economic limits to negative CO_2 emissions', Nature climate change, vol. 6, no. 1, 2016, p. 42-5; FAO, 2017, www.fao.org/nr/water/aquastat/water_use; S. Fuss, W. F. Lamb, M. W. Callaghan, J. Hilaire, F. Creutzig, T. Amann, T. Beringer, W. de Oliveira Garcia, J. Hartmann, T. Khanna, G. Luderer, G. F. Nemet, J. Rogelj, P. Smith,, J. L. Vicente Vicente, J. Wilcox, M. del Mar Zamora Dominguez and J. C. Minx, 'Negative emissions – Part 2: Costs, potentials and side effects', Environmental Research Letters, vol. 13, no. 6, 2018, p. 063002; Climeworks, 'Cost target for large scale plants.*

Compared to other CDR approaches current amine based low temperature DAC systems like the one Climeworks uses has the advantage of a very small footprint and does not need fresh water, and has negligible negative effects on ecosystems, at least on a Gt scale compared to other approaches(see Figure 16). There might however be local effects from building the plants and corresponding infrastructure. Lastly being a technology based approach that is not dependent on vast arable Land (or biomass), unlike biomass based CDR approaches DACS will if successfully implemented at scale become cheaper over time. Also it is worth noting that mitigation will likely become more expensive over time as the cheapest options will be exhausted first.

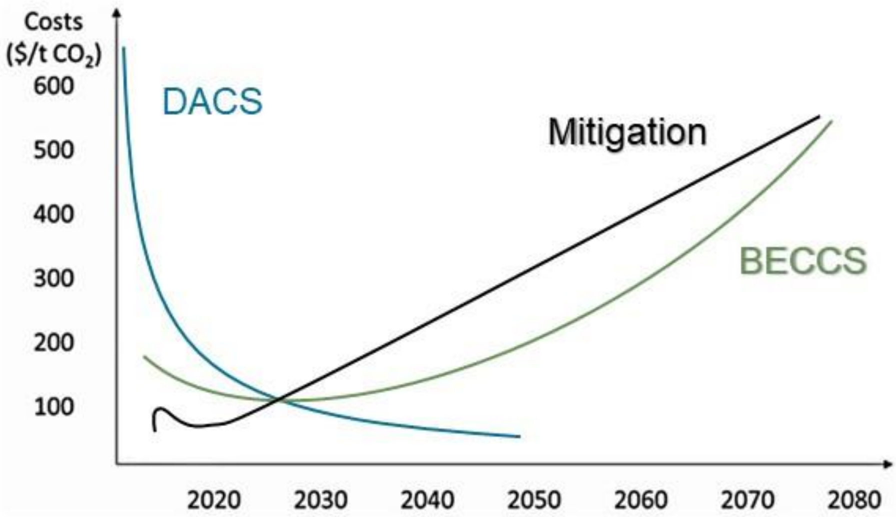

Figure 17. Development of costs of BECCS, DACS and classical mitigation over time assuming strong political will to cover mitigation costs. Note: Curves are indicative.[84]

2.6.4 Risks

At gigatonne scale amine based low temperature DAC requires large amounts of low or zero carbon renewable energy to operate and hence scale up depends on the availability of such energy sources. High temperature DAC via hydroxide solutions has a different risk profile as it requires large amounts of fresh water and hence faces resource constraints similar to those of BECCS. Also high temperature DAC is dependent on natural gas as an energy feedstock which might likely face resource constraints and drives down net-negative emissions effectiveness as the fossil CO_2 from the natural gas needs to be co-captured and sequestered again. While a number of those DAC applications have been piloted in actual operating conditions and some first steps have been taken on the path to commercial viability, a technology push is not sufficient. The biggest risk for market diffusion is a lack of large-scale market pull.

Large-scale demonstrations are required to prove that economies of scale and scope can drive cost down to meet CO_2 avoidance costs, which the market is willing to bear today. Notable exceptions are a few choice niche markets such as the food & beverage industry, which is willing to pay a substantial premium for high-purity food-grade CO_2. A continued absence of strong (CO_2) price signals, in all likelihood delivered by regulatory efforts, may stall an inherently attractive DAC technology and emerging market.

Technically the biggest risks are the inability to achieve energy efficiency gains in the process and the inability to drive down DAC unit manufacturing cost to eventually meet market expectations.

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[84] *Figure by Climeworks based on: M. Honegger and D. Reiner, 'The political economy of negative emissions technologies: consequences for international policy design', Climate Policy, vol. 18, no. 3, 2018, p. 306-321.*

2.6.5 Technological Readiness, Barriers and Open Questions

DAC technology operates at a small industrial scale in Switzerland and may enter and diffuse in niche markets where CO_2 can be sold at a premium. Several customers already purchase air-captured CO_2 (e.g. the agricultural sector for use of CO_2 as a fertiliser in greenhouses; the food & beverage industry to carbonate water).

There should be no risks for small-scale deployment especially when it is combined with surplus heat from other industrial processes and renewable electricity. The technology is currently being run in 14 different locations in several countries by Climeworks.

The two main factors that limit a large-scale deployment of the DACS technology in Switzerland are i) lack of sufficiently explored permanent storage capacities and ii) high costs compared to other CDR approaches.

Studies suggest a theoretical potential to store around 2.5 billion tonnes of CO_2 underground in saline aquifers at depths between 800 and 2'500 m in Switzerland.[85] Currently research is underway to assess the behaviour of rock formations that may serve as seals overlying the saline aquifers into which supercritical CO_2 is injected.[86] Owing to the lack of incentive, no CO_2 storage project is currently planned in Switzerland. Also Switzerland has only negligible and hard to access rock formations that are suitable for rapid permanent mineralisation such as ongoing in Iceland. However, this needs to be further explored. In densely populated areas for storage it is important to not only take geological and technological considerations into account but social concerns as well. One advantage of DAC is that there is no transportation of CO_2 needed because CO_2 can removed from ambient air directly at any location on the planet including all possible storage sites. This is possible because in ambient air, CO_2 is nearly evenly distributed around the globe at average concentrations of, at present 405.5 parts per million (and rising)[87] [88]. This means that for DACS especially international or cross-national CDR eligibility is important. In other words until underground storage capacities are sufficiently explored and proven, Switzerland is able to benefit from CDR/DACS activities in other countries and account the corresponding emission reductions to its nationally determined contributions. This mechanism is in principle supported by the Paris Agreement but needs to be strengthened (see also chapter 2.9).[89]

Globally there is almost limitless storage potential. For example basalt has enormous CO_2 storage potential comprising around 60% of Earth's surface and storage capacities of around 13.800 to 127.800 Gt of CO_2 have been estimated in deep-sea basalt reservoirs[90]. This is further backed up by a recent report of the US National Academies of Sciences who also come to the conclusion that storage is not a limiting factor.[91]

Furthermore, investments in Power to X projects that include DAC technology can offer a substantial mitigation potential and at the same time contribute to the development of DACS. This is crucial to unlock the future removal potential of the technology and for Switzerland to benefit from its leadership role within the field.

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[85] *Chevalier et al., 2010*

[86] *SCCER-SoE, 'ELEGANCY: CO_2 storage project in Mont Terri', 2019, www.sccer-soe.ch/research/pilots-demos/elegancy.*

[87] *There is regional and seasonal variation, of several ppm, which affects DAC only marginally. The variability in near surface CO_2 concentrations is visualized on the cover of the Royal Society report on Greenhouse Gas Removal: https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf*

[88] *World Meteorological Organization, 2019*

[89] *Paris Agreement (2015). Article 6, paragraph 2, 3 and 4.*

[90] *B. Callow, I. Falcon-Suarez, S. Ahmed and J. Matter, 'Assessing the carbon sequestration potential of basalt using X-ray micro-CT and rock mechanics', International Journal of Greenhouse Gas Control, vol. 70, 2018, pp.146-156.*

[91] *National Academies of Sciences, Engineering, and Medicine, 'Negative Emissions Technologies and Reliable Sequestration: A Research Agenda', Washington, DC: The National Academies Press, 2019.*

Permanent CO_2 storage in construction materials (see chapters 0 and 2.9.3) is a possibility that could be available in the near future already. Although storage capacities remain unknown for CDR at a larger scale in Switzerland, the combination of CO_2 storage in materials with DAC supports the development of large-scale DACS in the future.

As of today total costs to permanently remove one tonne of CO_2 from the air with Climeworks technology range from 600 to 800 CHF depending on the size of the plant. Other DAC companies have no commercial applications yet so it is not possible to give estimates. Climeworks estimates that these are likely going to decrease over the next years to around 100 CHF per tonne of CO_2 due to the further development of the technology and economies of scale. This is verified by a paper by David Keith of Carbon Engineering et al., estimates future DAC prices in the range of 94 to 232 US dollars per tonne.[92]

Open questions include the removal potential in Switzerland, due to constraints of geological storage, as well as how to ensure the use of low carbon renewable energy only, whilst not limiting deployment.

[92] *D. W. Keith, G. Holmes, D. S. Angelo and K. Heidel, 'A Process for Capturing CO_2 from the Atmosphere', Joule, vol. 2, no. 8, 2018, p. 1573-1594.*

2.7 Bioenergy with Carbon Capture and Storage (BECCS)

BECCS is the combination of two well-known technologies for climate change mitigation and may play a role in managing an emission overshoot. There are two acronyms widely and interchangeably used when coupling the two technologies: “BECCS” or “Bio-CCS”. BECCS is sometimes used to refer to the combustion of biomass for energetic use (heat and power) whereas Bio-CCS includes for example the algal biomass as a feedstock for the production of plastics, transportation fuels, animal feed and other chemical feedstock. In this report we use BECCS in a broad sense to include a range of feedstock, production methods, products and a broad range of end use. We also refer to CO_2 storage as opposed to “sequestration” owing to denotational and connotational ambiguity when using the word “sequestration”.

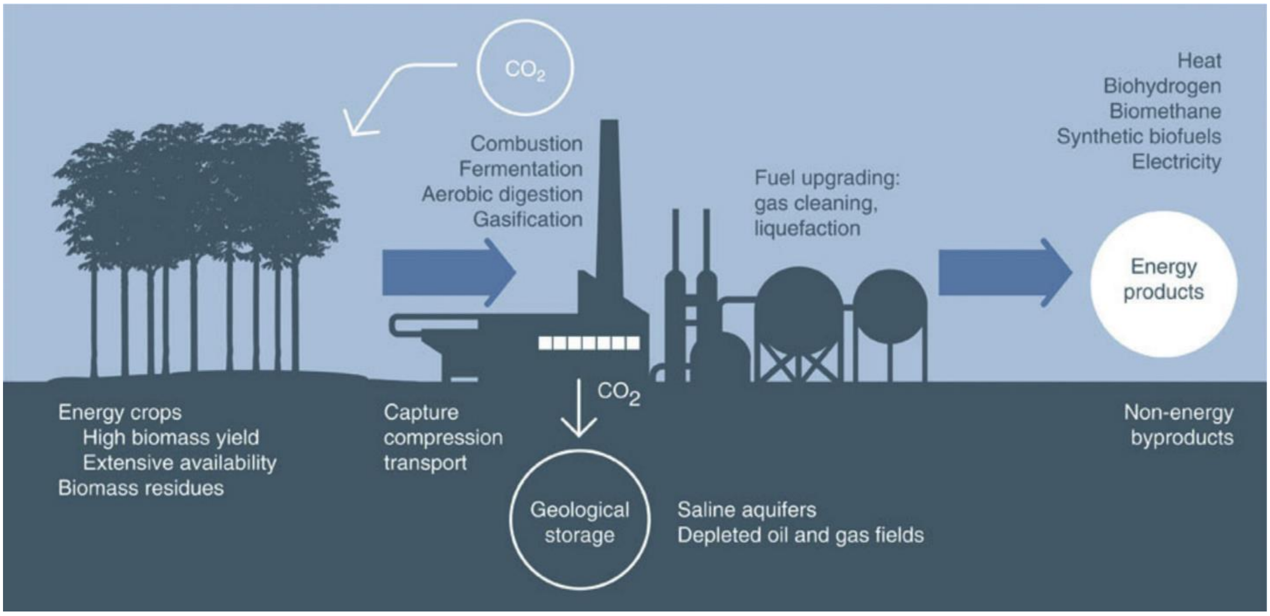

Figure 18. The Concept of BECCS.[93]

The concept of BECCS includes the entire value chain (Figure 18) and serves to illustrate that individual elements of the BECCS process are tried, tested and widely deployed across the world. However, integrating the elements into the complete BECCS value chain has only been executed in a small number of pilot and demonstration projects. Currently there are no BECCS projects in Switzerland and hence no stakeholders from Swiss based BECCS projects could inform this dialogue. UK-based Drax commenced Europe's first BECCS project in May 2018.[94] BECCS may however be a future option in Switzerland, especially in waste-to-energy plants that co-fire biomass alongside other waste.

2.7.1 Approach

Essentially, BECCS removes CO_2 from the atmosphere and may thus give rise to net-negative GHG (mostly CO_2) emissions. BECCS has a broad range of applications and correspondingly a wide potential of deployment. BECCS may act as an integral part in the supply of heat and electricity when

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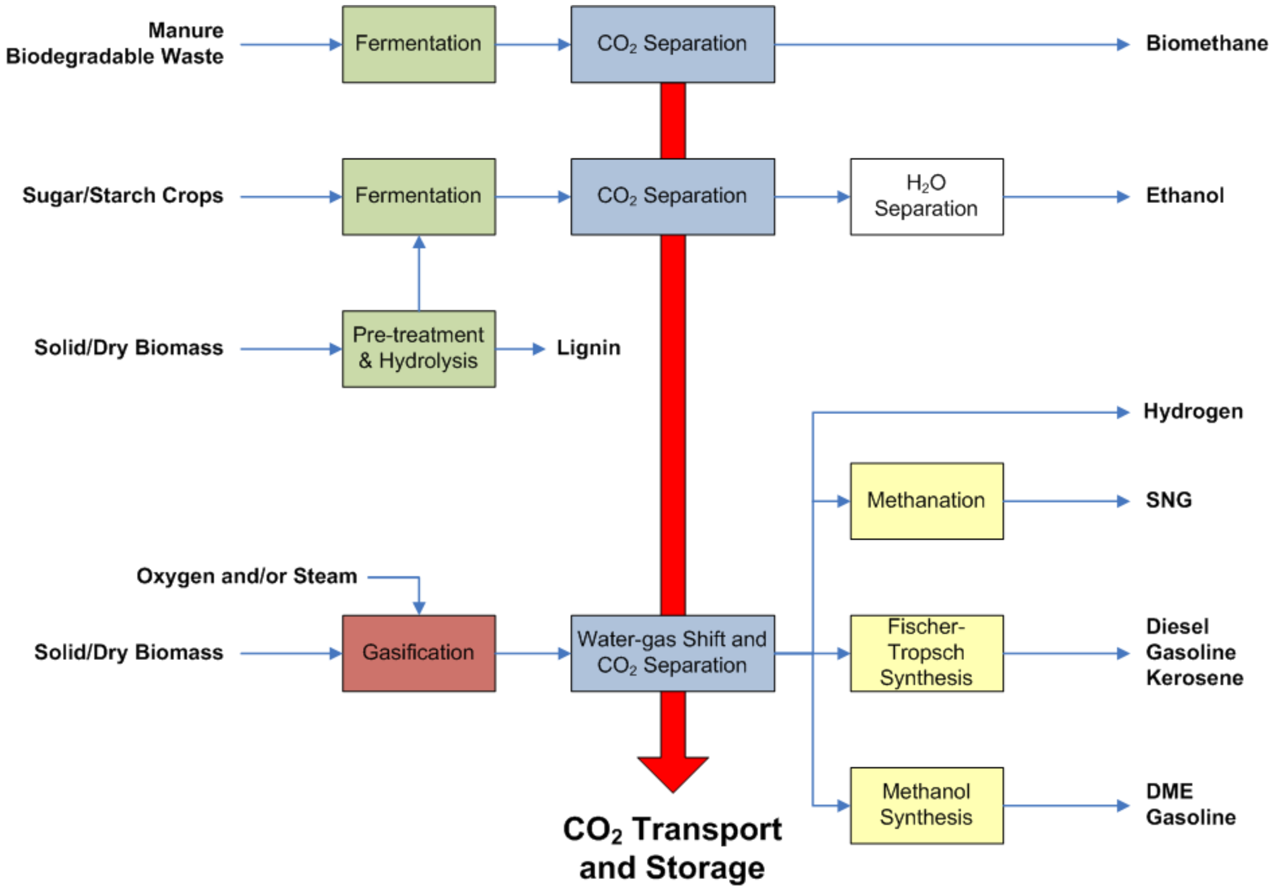
[93] Kemper, J., 'Biomass and carbon capture and storage – a review', International Journal of Greenhouse Gas Control, vol. 40, 2015, p. 401-430.

[94] Green Car Congress, 'Drax, C-Capture to pilot Europe’s first bioenergy carbon capture storage project', 2018.

deployed in combined heat and power plants, in the paper and pulp industry, in lime kilns for cement production, in the production of ethanol or in biogas plants or bio-refineries.

Feedstocks such as oil crops, sugar and starch crops, lignocellulosic biomass from forestry, agriculture and other industries as well as biomass from waste undergo a variety of production processes to be converted into products. The production processes and technologies may encompass trans-esterification, fermentation, advanced biofuel processing, chipping, palletisation, pyrolysis, gasification, sorting, separating and fuel preparation, and anaerobic digestions. Products comprise a wide range of heating and transportation fuels, ethanol, woodchips, pellets, pyrolysis oil, bio-based syngas, refuse derived fuels and biogas.

Carbon capture technologies may be deployed in a wide range of production processes that convert biomass into products. Options include capturing CO_2 during the fermentation process, during gasification and combustion including oxyfuel (combustion in the presence of oxygen as opposed to air) and in industrial processes. Compression and storing (the captured) CO_2 are again process steps that are widely deployed in a number of industries. As described above, it is the combination of all BECCS process elements, which is at the pilot and demonstration stage with active research to develop next generation BECCS technologies that make BECCS commercially viable and reliable while maintaining safety (Figure 19).



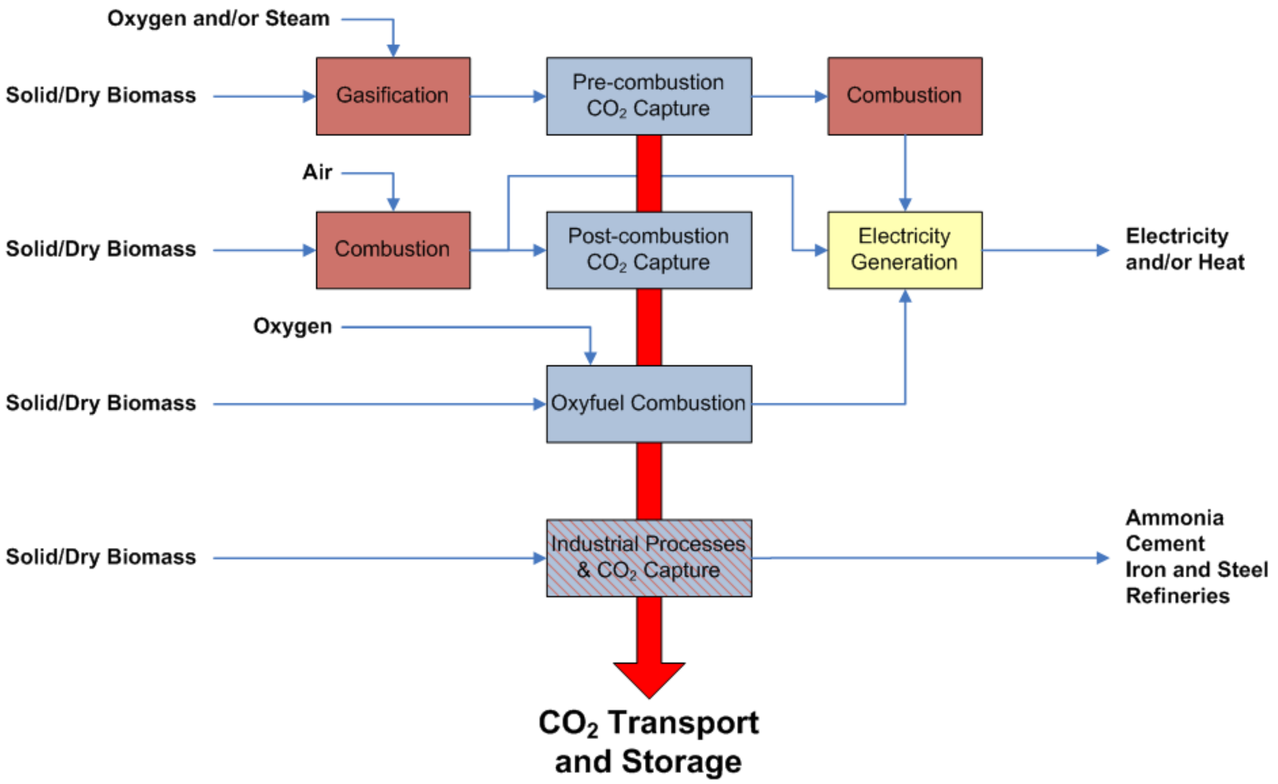


Figure 19. CO_2 capture technologies allow CO_2 to be separated from the process.[95]

2.7.2 State of Development

Since being first developed some 20 years ago, there has been considerable activity in research and innovation, which has resulted in about 5 BECCS projects in operation, capturing each between 0.1-0.3 million tonnes of biogenic CO_2 per year[96]. The Illinois Basin Decatour Project being followed up by the Illinois Industrial CCS Project, the largest and highest profile venture storing about 1 million tonnes per year of biogenic CO_2 in a deep saline aquifer with a current license for 5.5 million tonnes of CO_2 stored. At this plant CO_2 is captured from ethanol production during the fermentation stage – a cost-effective and efficient capture point owing to the high CO_2 concentration in the exhaust gas. In Europe, the Drax power station has deployed a low cost capture technology on a biomass power plant to pilot the capture component of a first-of-a-kind net-negative biomass power plant.

2.7.3 Opportunities

The global technical BECCS potential (relying on sustainably produced biomass) has been estimated by the IEA Greenhouse Gas Technology Collaboration Program (IEAGHG) to about 10 billion tonnes of CO_2 per year with an emphasis on gasification and combustion of biomass in BECCS[97]. More recent estimates are in the range of 1-5 billion tonnes of CO_2 per year that BECCS might remove[98]. The potential in itself presents a major opportunity, which needs to be further pursued and

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[95] *M. Cabo, 'Policy and Technology Challenges for Bio-CCS', Presentation during the EU Sustainable Energy Week, ECN The Netherlands, 2012.*

[96] *C. Consoli, 'Bioenergy and Carbon Capture and Storage', Global CCS Institute, 2019.*

[97] *IEAGHG, 'Potential for Biomass and Carbon Dioxide Capture and Storage: Report 2011/06', 2011.*

[98] *M. Fajardy and N. Mac Dowell, 'Can BECCS deliver sustainable and resource efficient negative emissions?', Energy & Environmental Science, vol. 10, no. 6, 2017, p. 1389-1426.*

refined. However, as with all other technologies BECCS is not the "silver bullet" but needs to be judiciously studied and assessed on a project-by-project basis prior to deployment. No figures exist for Switzerland because stakeholders fundamentally have not believed that CCS is part of the solution to avoid or lower GHG emissions let alone remove CO_2 directly or indirectly from the atmosphere. Although a fallacy and driven by NGO sentiments, public perception in Switzerland has persistently considered CCS to be a technology only applicable to coal-based power generation[99].

2.7.4 Risks

There are a number of challenges related to BECCS being ultimately able to deliver sustainable and resource efficient negative emissions and thus contribute to the CDR technology portfolio. BECCS is not without controversy and naturally, there are a number of synergies and trade-offs when considering the United Nations Sustainable Development Goals.[100] Land competition for food production, for example, as well as CO_2 emissions associated with biomass cultivation, harvesting and processing need to be included in a mandatory LCA to assure that BECCS is indeed a sustainable solution to mitigate climate change. The BECCS research and industry community has recognised that detailed assessments are necessary.

One challenge relates to the fact that introducing CCS on biomass use comes with a penalty in terms of efficiency: CCS processes themselves require energy, which in turn is derived from biomass feedstock and its qualities; the penalties depend on many factors but may range from 4-10% for the case of power generation from biomass with CCS.[101] Unless biomass is sourced in a sustainable manner, BECCS may impose strain on water resources (agriculture and power generation – if BECCS was to be deployed on power generation facilities – are both water-intensive industries). In addition, the biomass supply chain may result in a substantial amount of direct and indirect GHG emissions (land use change resp. indirect land use change) which counter BECCS' ability to deliver net CO_2 removal.

It is clear that whole-system assessments of the BECCS supply chain, accounting for the cultivation, harvesting, processing, transport, and conversion of biomass and the subsequent separation, transport and storage of CO_2 are required.

Making BECCS happen is not primarily about CO_2 capture technology, but about systematising the policy framework around BECCS and developing transport and storage infrastructure needed for large-scale implementation. In addition, in order for BECCS to offer negative CO_2 emissions, the biomass utilised must be sustainable, and sustainable biomass for use in BECCS comes with a limit. Currently, there is no incentive for a bio-based industry to capture and store CO_2. In order to be able to invest in and realise BECCS and negative emissions, some major prerequisites would include:

- Policy instruments and market conditions: Accounting for negative emissions in emission trading systems or otherwise enabling the development of business cases will be indispensable for industries to voluntarily invest in carbon negative technologies. Policy instruments should be adaptable to new developments and changes in markets conditions.
- Political stability: Policy instruments that facilitate long-term strategies and build confidence are needed for large-scale investments.
- Defined standards and frameworks: Uncertainties remain among undefined characterisations of BECCS and introducing Utilisations ("U") to yield BECCUS (Bioenergy with carbon capture and utilisation) and other related terms such as biofuels and sustainable biomaterial. Establishment of common definitions would bring consistency to the discussion.

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[99] Greenpeace, 'Die CCS-Technologie gaukelt wirksamen Klimaschutz vor', 2008, www.greenpeace.ch/de/story/17690/die-ccs-technologie-gaukelt-wirksamen-klimaschutz-vor.

[100] IPCC SR15, 2018.

[101] IEAGHG, Potential for Biomass for Carbon Dioxide Capture and Storage, 2011/06, July 2011.

2.7.5 Technological Readiness, Barriers and Open Questions

Full-chain BECCS technologies are today at the stage of piloting (TRL 4-6) with certain geographic regions (North America, The Illinois Industrial Carbon Capture and Storage Project) deploying specific BECCS technologies in large-scale demonstration projects at TRL 7-8.

The situation in terms of commercial readiness is less advanced. Indicative cost estimates range from 30-250 US$ per tonne of CO_2 that vary significantly in terms of specific technologies deployed and on location.[102] Today, there is little incentive for industries to become active.

While there is no scientific or technical (engineering) showstopper, considerable research and innovation is necessary to engage in a path to commerciality. A number of actions are necessary especially in Switzerland where there has been little concerted effort expended on BECCS (particularly for the case of waste-to-energy plants with 50-60% of the feedstock being biomass):

- Obtain a good understanding of realistic potential of different solutions with associated cost reduction paths for Switzerland.
- The policy framework should enable low threshold implementation of first mover projects usually via subsidies. This would support both the deployment of negative emissions and development of Carbon Capture and Utilisation (BECCUS) technologies.
- There is a need for funding of non-technical projects that address the complex nature of BECCS deployment.
- Detailed studies on advantages and disadvantages of BECCS such as biomass availability and use, trade-offs in terms of sustainability criteria, impacts, etc.
- CO_2 storage (confidence) remains unknown for BECCS application in Switzerland (as well as for conventional CCS) and must therefore be addressed at a different level than at the scale of an individual project basis. On the one hand, Switzerland's geothermal exploration program offers opportunities to characterise a number of saline aquifers not only in terms of their geothermal potential, but also in terms of their CO_2 injectivity and storage potential. This must be coordinated. Storage sites have to be treated as an independent service to customers wishing to pass on their captured CO_2 for storage provided by other service providers. Industries operating government and public funding must take an active role in establishment of CO_2 hubs and larger infrastructure in order to facilitate the entire CCS value chain from capture to storage. This would enable the participation also from smaller companies who individually will not be able to establish a CCS chain.

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[102] *C. Consoli, 'Bioenergy and Carbon Capture and Storage', Global CCS Institute, 2019.*

2.8 Enhanced Carbon Uptake via Cement

In Switzerland, a number of projects investigate permanent CO_2 storage in building materials. Those approaches come with three key advantages. Firstly, they allow for permanent fixture of CO_2 in building materials without the need for underground storage. Secondly, they come with an inherent economical value as CO2 can be sold a production resource. Thirdly, if atmospheric CO_2 was used, such approaches would for negative emissions.

2.8.1 Approach

Production of cement is a carbon intensive process. Although the Swiss cement industry is leading globally in terms of sustainability and has reduced its emissions by about two thirds since 1990, it still makes up for about 9% of Switzerland's CO_2 emissions. During the production of cement, CO_2 is essentially emitted in equal parts in two process steps. First, CO_2 is released by burning fuels in order to heat the lime kiln to a temperature of about 1'450 ºC. Second, CO_2 is released as calcium oxide is produced from calcium carbonate (i.e. limestone) in the kiln. The chemical reaction is

$$CaCO_3 \rightarrow CaO + CO_2$$

Cement is the key ingredient for the production of concrete. The calcination reaction is reversed over time, once cement is exposed to atmospheric CO_2 as part of a concrete construction. A front of carbonated concrete first builds up on the outward-facing surface, and then slowly moves inside the concrete element. The speed at which this carbonation front moves into the concrete is well understood and essentially depends on the exposure of the concrete construction as well as on the concrete strength indicated in Megapascal (MPa) in Table 20 below.

Strength	< 15 MPa	15-20 MPa	25-35 MPa	> 35 MPa
Wet/submerged	2 mm/ $\sqrt{year}$	1.0 mm/ $\sqrt{year}$	0,75 mm/ $\sqrt{year}$	0,5 mm/ $\sqrt{year}$
Buried	3 mm/ $\sqrt{year}$	1.5mm/ $\sqrt{year}$	1.0 mm/ $\sqrt{year}$	0.75mm/ $\sqrt{year}$
Exposed	5 mm/ $\sqrt{year}$	2.5 mm/ $\sqrt{year}$	1.5 mm/ $\sqrt{year}$	1 mm/ $\sqrt{year}$
Sheltered	10 mm/ $\sqrt{year}$	6 mm/ $\sqrt{year}$	4 mm/ $\sqrt{year}$	2.5 mm/ $\sqrt{year}$
Indoors	15 mm/ $\sqrt{year}$	9 mm/ $\sqrt{year}$	6 mm/ $\sqrt{year}$	3.5 mm/ $\sqrt{year}$

Table 20. Carbonation rates for exposed concrete based on CEM I cement.[103]

In recent years, CemSuisse (industry association of Swiss cement producers) commissioned several studies in order to estimate the total amount of CO_2, which is taken up by concrete constructions in Switzerland as of today. The summary findings of the study undertaken by EMPA and TFB AG are shown in Figure 21.

[103] *B. Lagerblad, 'Carbon dioxide uptake during concrete life cycle: State of the art', Stockholm: Swedish Cement and Concrete Research Institute, 2005.*

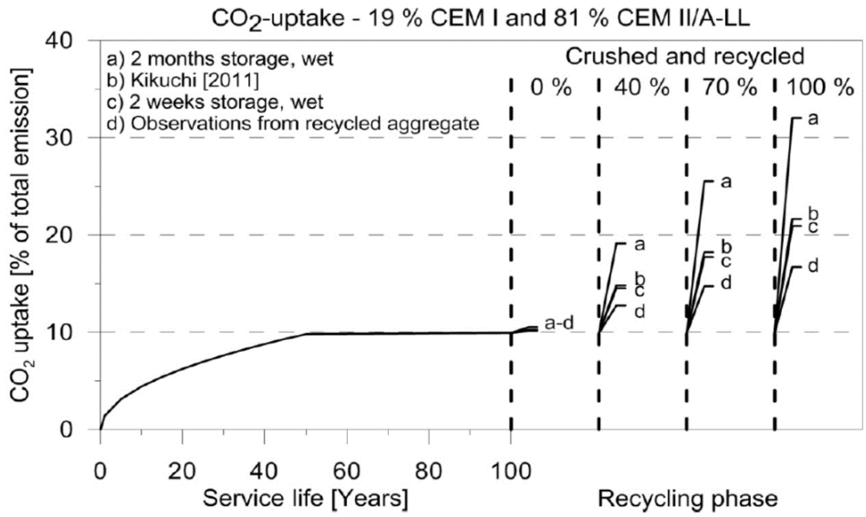

Figure 21. CO_2 uptake of concrete in Switzerland.[104]

The authors of the study estimate that only about 10% of the total CO_2 emissions from cement production are rebound to concrete over the service life of concrete. Another 5% of emissions are reversed as concrete is exposed to atmospheric CO_2 during the concrete recycling process (lined in Figure 21 above).

If the calcination reaction was fully reversed, the CO_2 uptake would amount to about 65%. Concrete therefore holds a significant and underutilised CO_2 storage potential – especially after its service life during the recycling phase. If all demolished concrete in Switzerland was fully carbonated, up to 2.5 million tonnes of CO_2 could be stored annually by the year 2050 as shown in Figure 22 below.

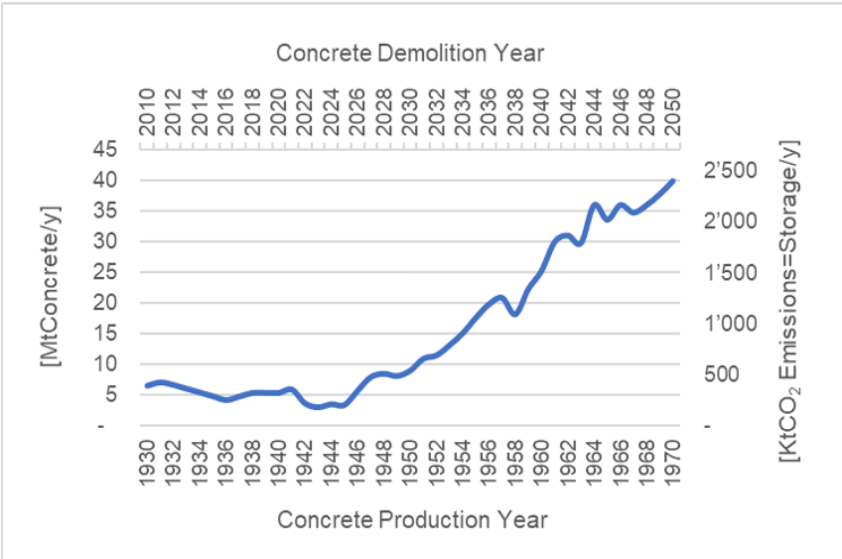

Figure 22. Past concrete production and potential future CO_2 storage in Switzerland.[105]

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[104] A. Leemann and F. Hunkeler, 'Carbonation of concrete: assessing the CO_2-uptake', 2016, www.cemsuisse.ch/cemsuisse/forschung/forschungsberichte/berichte_2016/index.html?lang=de

[105] Carbon Dioxide Information Analysis Centre 2019: T. A. Boden, G. Marland and R. J. Andres, 'Global, regional, and national fossil-fuel CO_2 emissions', Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tenn., USA, 2009

Figure 22 allows to estimate the future CDR potential based on past CO_2 emissions from cement production assuming an average service life of concrete of 80 years and an average of 60 kg of CO_2 emitted per tonne of concrete produced.

Today demolished concrete is crushed at concrete plants and stored on uncovered piles until it is reused as a construction aggregate. During the storage phase, CO_2 uptake is inhibited as firstly, close to no atmospheric CO_2 can diffuse inside the piles and secondly, water on the materials' surface significantly slows down the carbonation reaction. Several approaches to enhance CO_2 uptake of concrete during the recycling phase are currently being developed in Switzerland and described in section 2.8.2 below.

The European industry association of cement producers (Cembureau) has suggested a protocol on how to account for CO_2 uptake in cement in domestic and international GHG inventories[106]. CO_2 uptake in cement depends largely on how concrete rubble is handled and stored as well as on climatic conditions such as temperature and humidity. For the protocol to be followed in Switzerland, one therefore needs to compare the assumptions made by Cembureau with local conditions in Switzerland.

2.8.2 State of Development

Two main technologies for enhanced carbon uptake in cement are currently being developed in Switzerland. The process of Zurich-based Sika Technologies AG (patent application "US2016046532"), part of a concrete recycling technology, exploits synergies with a chemo-mechanical treatment of concrete demolition waste. It involves a superficial carbonation of the cementitious matrix that is softened and removed upon attrition. Freshly exposed surfaces are obtained, which can further undergo carbonation until aggregates, free from cementitious material, are obtained. Concrete/mortar demolition waste can thus be separated into "secondary aggregates" for recycling at a quality level that of primary material, and a powdery material, which may be used as secondary raw materials in a broad application spectrum.

Bern-based Neustark GmbH follows a different technological approach, which has been developed at ETH Zurich since 2017. The technology, which is illustrated in Figure 23 below is designed for seamless integration with current processes at concrete plants by directly carbonating the crushed concrete material in a reactor without removing cement from the gravel aggregate.

Figure 23. Visualisation of Neustark's technology deployed at commercial scale.[107]

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[106] *H. Stripple, C. Ljungkrantz, T. Gustafsson and R. Andersson, 'CO_2 uptake in cement-containing products: Background and calculation models for IPCC implementation', Commissioned by Cementa AB and IVL research foundation, 2018.*

[107] *Neustark, 2019.*

Neustark's technology has been deployed for the first time at a commercial environment at a concrete production plant in Bern in March 2019. The results of the test run suggest that based on current concrete recycling processes, Neustark's process allows the storage of about 15 kg of CO_2 per tonne of demolished concrete, which corresponds to a national carbon dioxide removal potential of 75'000 tonnes of CO_2 based on todays' concrete demolition amounts (see Figure 22).

Figure 24 shows a concrete particle processed using Neustark's technology, subsequently cut in half and sprayed with a pH-indicator.

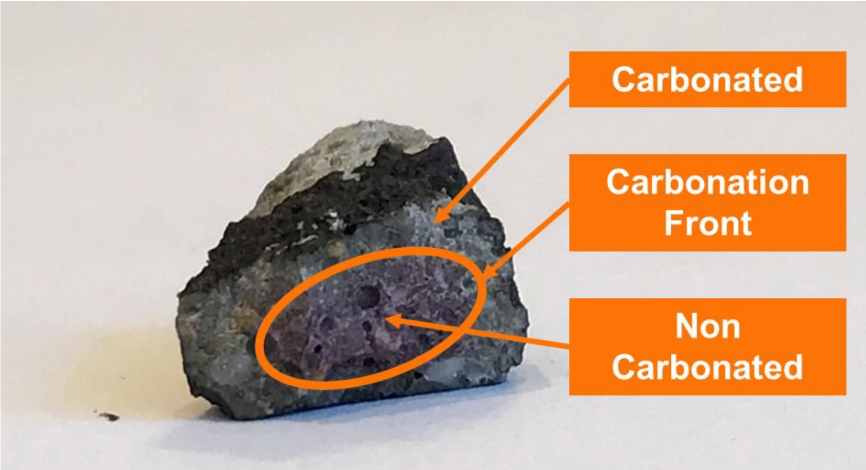

Figure 24. Carbonation of crushed concrete particle following a Neustark process treatment. The grey/non-red area was carbonated through Neustark's process with the red oval indicating the edge of the carbonation front.[108]

There are other international efforts underway to enhance CO_2 uptake in cement. Similar to Sika and Neustark, the USA-based Blue Planet stores CO_2 in concrete waste aggregates. The Canadian company Carbon Cure pursues yet another approach by directly injecting CO_2 gas in fresh concrete directly at the concrete batching plant.

Cement and concrete rubble is the most voluminous but not the only mineral waste with a potential for CO_2 -uptake. The development of carbon negative construction materials from raw materials such as waste incineration slags or serpentine minerals include Carbon8 (UK), Solidia Technologies (USA), Carbstone (Belgium), and Mineral Carbonation International (Australia).

2.8.3 Opportunities

The goal of either approach described above is to reverse emissions from cement production. As such these are no negative emissions technologies. However, enhanced CO_2 uptake via cement represents a domestically available and socially accepted solution for storage of CO_2 and thus is an attractive downstream complement to "upstream" negative emissions approaches such as DACS or BECCS.

In order to generate negative emissions, the cement sector needs to combine the following three measures:

1. Enhanced CO_2 uptake via cement
2. Application of 100% renewable heating fuels for production of fresh cement
3. Deployment of CCS technology at cement production plants

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[108] *Neustark, 2019.*

The combination of renewable heating fuels and CCS for concrete production may result in a special form of BECCS or CDR technology. Given sufficient sustainable biomass as a feedstock, cement may be a carbon negative material once it leaves the production facility and may become even more carbon negative as it binds CO_2 during its service life as well as in the recycling phase.

2.8.4 Risks

The limiting factor for enhanced CO_2 uptake via cement is the amount of available demolished concrete in Switzerland. Today, demolished concrete is collected, crushed and stored by several hundred concrete producers in Switzerland. Unlocking the CDR potential of concrete therefore requires the collaboration of many individual businesses, which in turn is only possible with business models that offer sufficient incentives.

2.8.5 Technological Readiness, Barriers and Open Questions

The Sika process has been proven to return “clean aggregates” on a lab scale, corresponding to TRL 4.

As of summer 2019, Neustark’s technology has a TRL of 5 with a first successful pilot deployment in a commercial environment. The first commercial-scale deployment at a TRL of 9 is planned by the year 2020 in Switzerland with a commercial value proposition being on the horizon. According to the technology developers, the main barrier to the widespread deployment of the technology is the fact that technical CO_2 sinks do not qualify as carbon reductions under the pre-2020 Swiss CO_2 law. If this barrier was removed, the deployment of the solution would only be limited by the amount of available demolished concrete in the country. As shown in chapters 2.8.1 and 2.8.2, current concrete demolition amounts hold a potential for removing about 75’000 tonnes of CO_2 annually as of today, which could go up to about 2.5 million tonnes CO_2 until the year 2050.

Open questions concern the monitoring of the CO_2 uptake. Firstly, a reliable reference scenario needs to be developed. For this, the existing CemSuisse studies on CO_2 uptake of concrete present a reasonable starting point. The studies mostly need to be complemented by representative carbonation measurements of actually recycled concrete aggregates. Second, protocols for the measurement of additional CO_2 uptake need to be developed and verified. For both the Sika and Neustark processes, monitoring can be very transparent by measuring the consumption of CO2 inside the reactors Those protocols need to be specific to the relative technological approach. For the Sika process, CO_2 uptake can be measured by the consumption of concentrated CO_2 in the reactor. For Neustark’s technology, two complementary measurement options exist: firstly, the CO_2 concentration of air that is circulated through the concrete piles can be measured. Secondly, the carbonation degree of the treated aggregates can be monitored through continuous sample measurements.

2.9 Permanent Non-Soil Based CO_2 Storage Options for Switzerland

For negative emissions to be realised via the removal of CO_2 from the atmosphere by technological means (i.e. by DACS) or extracting it from the combustion of biomass (BECC) a sufficient, safe and permanent storage options need to be available or developed. Chapter 2.9 briefly discusses three potentially promising options.

2.9.1 Geological Storage in Switzerland

Many decades of injecting CO_2 in deep underground formations all over the globe have led practitioners and regulators to the conclusion that CO_2 storage is a safe operation if storage sites properly selected, characterised and managed.

While Switzerland has deep saline aquifers[109] that act as potential storage reservoirs for injected CO_2, there is little knowledge about specific sites suitable for CO_2 storage. Such sites need to fulfil a number of criteria: CO_2 injectivity tests need to confirm the presence of saline aquifer/reservoir rock that occur below associated seals provided by tight cap rocks. Reservoir-seal couples need to be confirmed at depths between 800 and 2’500 m. The temperatures in these rocks should be determined by low geothermal gradients (°C per km depth) giving rise to temperatures between 20-70 °C, as opposed to high gradients which are suitable for geothermal energy utilisation (usually above 60 ˚C). However, there are utilisation concepts where both geothermal energy utilisation and CO_2-storage may be realised in the same rock formations. Another site-specific criterion is the tectonic setting, the presence of faults, and the state of stress – all of which govern the “ease” with which CO_2 can be injected and its migration paths controlled. Ultimately, the physical properties of the respective rock formations, their permeability and porosity, their injectivity and so on are also factors that govern the amount of CO_2 that can be ultimately stored[110].

It is in all likelihood not a question whether (or not) suitable storage sites exist but very much “where”. With Switzerland’s current subsidy programs to characterise the subsurface for geothermal energy utilisation, there is an excellent opportunity to co-investigate at the same time the suitability for for CO_2 storage. If such a path is pursued in populated areas, it is vital that considerations around public acceptance are taken into account.

2.9.2 International Geological Storage Under the Paris Agreement

In recent years, underground storage in the form of rapid mineralisation has been achieved outside of Switzerland, for example with the CarbFix and CarbFix2 projects in Iceland (see chapter 2.6.2 – CDR via DACS). This adds another type of storage option (international) where the geology is suitable.

The Paris Agreement does allow for CO_2 removal and storage outside of a nation's boundaries provided that both parties (nations) agree and – to avoid double counting – accounting is overseen by an external body (Article 6.2, 6.3, 6.4[111]). This means that storage can be sited where it is safest and most accepted and not be confined by national boundaries – a number of countries surrounding the

[109] G. Chevalier, L. W. Diamond and W. Leu, 'Potential for deep geological sequestration of CO_2 in Switzerland: a first appraisal', Swiss Journal of Geosciences, vol. 103, no. 3, 2010, p. 427-455.

[110] Purely for illustrative purposes: about 100 million tons of CO_2 in liquid state may be stored in the available pore volume of 5 km long x 5 km wide x 50 m thick porous (15%) sandstone at a depth of around 1000 meters. In reality, the amount of CO_2 to be stored will be much less (2-10% of the value given) because of competing with water in the pore space; mineralization; and many other effects.

[111] *UNFCCC, 'Paris Agreement', 2015.*

North Sea currently undertake this approach (while adopted, the ratification of the London Convention and London Protocol[112] regarding transboundary CCS projects are ongoing, albeit very slowly). Switzerland should therefore investigate international CDR and storage opportunities as well. This approach is especially suited to DAC, as the technology can extract CO_2 directly from air at a suitable storage site. Thus eliminating the need for transportation et cetera of CO_2.

2.9.3 Permanent Storage in Materials and Products

Lastly, in recent years there has been substantial developments to design and develop a number of products such as synthetic building materials that would allow for a permanent storage of CO_2. Such products like these are particularly interesting for early stage CDR as they allow permanent storage of CO_2 without the need to develop geological storage projects, which can have long lead times. With material storage, the main prerequisite would be appropriate LCAs to ensure there is no delayed leakage from the materials.

[112] *IMO, 'Carbon Capture and Sequestration', 2019, www.imo.org/en/OurWork/Environment/LCLP/EmergingIssues/CCS/Pages/default.aspx, (accessed 10 July 2019).*

2.10 The Role of CDR Approaches in Mitigation and Power-to-X

Next to storing carbon dioxide in the ground, CO_2 can also be used to produce fuels and products, which is often referred to as power-to-x (PtX). Usually these fuels and products release the CO_2 back into the atmosphere at the end of their life and should therefore not be considered NETs. However using atmospheric carbon can replace fossil carbon and is hence an important mitigation technology for any net zero emissions pathway.

Futhermore, as sustainable PtX needs atmospheric CO_2 as a feedstock such approaches which could help scaling up CDR approaches such as DACS or BECCS. This is the reason why these approaches are covered in this report with a focus on fuels, despite being largely mitigation technologies rather than NETs.

PtX refers to technologies that convert electricity with water and carbon dioxide into i) energy carriers or products, ii) physical energy stores, and iii) CO_2 intensive products. These technologies could for example convert extra renewable energy in summer into useable fuels that can be either used directly or stored. This way it contributes to the balance of the grid.

Importantly in this way, energy from renewable sources can be used to indirectly electrify and thus decarbonise emissions from motor vehicles or in chemical products with high added value. Demand of ("fossil") carbon sourced from the earth may be successfully replaced by carbon sourced from the atmosphere via DAC or BECCS. In the case of synthetic building materials there is even a potential double benefit of both atmospheric CO_2 as a sustainable feedstock and permanent CO_2 storage in building materials and hence negative emissions. However, this needs to be verified.

2.10.1 Power-to-Gas, Power to Fuel and Power to Products

Typically in combustion, the chemical reaction of burning gases and fuels results in energy, CO_2 and H_2O in gaseous form. Power to gas and power to fuel reverse this process and combine H_2O and CO_2 with renewable energy. The final product is a synthetic gas or fuel that in terms of quality for the end consumer is in theory a perfect substitute of conventional fossil energy carriers with fewer side effects in terms of air pollution since synthetic fuels (called ReFuNoBio within EU legislation) cause less problems with impurities and consequently other pollutants.

Further advantages of synfuels could be an application in the transport sectors that have long been considered difficult to mitigate (aviation, maritime transport). The fuel can also be easily distributed within existing infrastructures. However, only if the CO_2 is derived from a non-fossil source, power-to-X will enhance carbon neutrality necessary for a successful net zero mitigation. The cost of these fuels depends on the cost of its feedstock, i.e. the CO_2 and renewable energy generation capacity. Furthermore, CO_2 from atmospheric sources, unless protected by legislation or LCAs, will not enter the market as they are immediately driven out because of their higher technological costs. Capturing CO_2 from fossil point sources (in other words being a by-product of combustion of oil, coal or any other given industrial process such as steel production), will always outcompete the cost structures of a feedstock that has to be grown, produced or captured from the air due to its higher concentration.

Atmospheric Carbon Capture and Utilisation (ACCU) could be used as a way of creating a carbon cycle similar to biomass conversion technologies. Here, the atmosphere acts like a carbon supply from which it is taken for utilisation and afterwards returned.

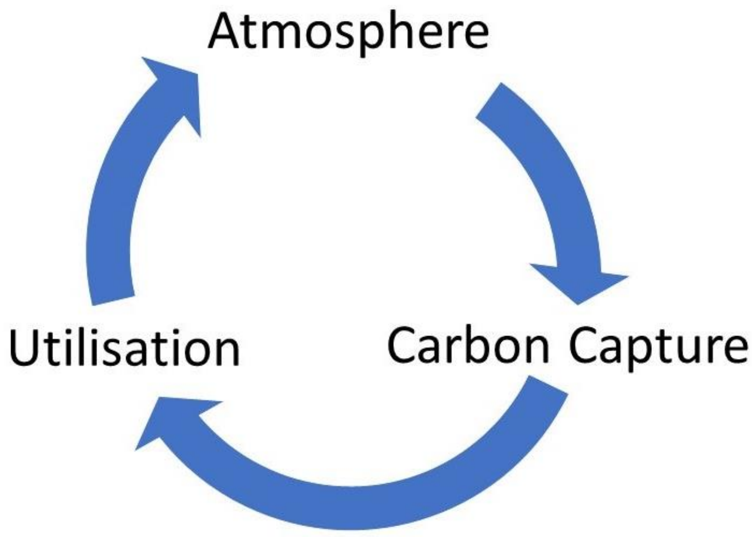

Figure 25. Closing the carbon cylce with ACCU.[113]

According to German energy agency DENA, in a net zero economy CO_2 could also become a supply problem, as the supply from remaining unavoidable point sources[114] of CO_2 are currently estimated to be less than 200 million t CO_2/year. Even the more conservative e-drive scenario of the study shows the EU demand for synfuels to exceed unavoidable sources around the year 2030. As seen in the figure below the majority of the CO_2 will then be sourced from the atmosphere. However, limits to PtX in general – and synfuels more specifically – are clearly set by the availability of renewable electricity sources. In their paper about carbon flows in Switzerland[115], Meier et al. conclude that if all extra power is used in a future energy system with 20 TWh/a PV and 4 TWh/a wind power, around 10% of the traffic on the streets could be fueled with syngas or synfuels. Therefore, the authors recommend to use synfuels only for those vehicles that are not easily decarbonised (i.e. planes, trucks, busses) and directly electrify all other transport.

Despite being a relatively new technology, there are already several PtX projects realised in Switzerland. The first Swiss power-to-methane pilot plant was built in Rapperswil by the Institute of Energy Technology[116] at the University of Applied Sciences of Eastern Switzerland in 2014. Another power-to-methane plant is currently being installed in Solothurn and part of the EU-funded project "STORE&GO".[117] In 2019, Limeco will put the first industrial power-to-gas plant into operation in Dietikon[118].

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[113] Risk Dialogue Foundation, 2018

[114] *Such as fossil power production and carbon capture thereof. This utilization of CO_2 from industry is incompatible with Paris*

[115] *Investigation of Carbon Flows in Switzerland with the Special Consideration of Carbon Dioxide as a Feedstock for Sustainable Energy Carriers; B. Meier, F. Ruoss and M. Friedl; Energy Technology, 2017, 5, 864 – 876*

[116] *Institute of Energy Technology (IET): www.iet.hsr.ch*

[117] STORE&GO project, see: www.storeandgo.info

[118] Limeco, 'Leuchtturmprojekt bei Limeco: Gemeinden sagen Ja zur schweizweit ersten industriellen Power-to-Gas-Anlage', 2018, www.limeco.ch/de/aktuell/pressemitteilungen/leuchtturmprojekt_power-to-gas-anlage,

2.10.2 Energy Storage/Grid Balancing

The aforementioned PtX approaches may also lead CDR technologies to become a key part of grid balancing. The resulting fuel does not necessarily need to be used in transportation, as other projects install the same approach in order to store electricity from renewable energy generation leading to a more stable electricity grid. Even without converting synfuels back into power, CCU technologies can add to grid balance by only obtaining power when there is an overproduction from renewable energy sources. The produced gas or fuel can then be used directly or stored for winter consumption.

2.10.3 CO_2 Intensive Products

PtX can also lead to a range of chemical materials and building materials. Most of these processes are currently at early stages of development. Schaub et al. provide an overview of possible applications to be further explored.[119] However, besides all current technological optimism in this field caution is advised, as CCU business cases alone will not provide enough volume for CDR approaches to become climate-relevant at scale for two reasons.

In summary, firstly, the amount of negative emissions needed will need to outpace global demand for CO_2 before 2050. For example, by far the largest market, the global market for atmospheric CO_2 for synthetic fuels is estimated to be at 2 Gt in the most favorable conditions.[120] Negative emissions are estimated to be at least 6 Gt by 2050.[121] Secondly, if not guided by suitable policy, CCU would not result in climate relevant CDR on a gigatonne scale, as CO_2 from atmospheric sources will always remain more expensive than point source capture (CCS) as it is literally chasing 400 part per million and not extracting fossil carbon from a highly concentrated flue gas stream. Furthermore, capturing atmospheric CO_2 has the potential to generate both negative emissions via storage and achieve carbon neutrality via use. In contradiction recycling and reutilisation as suggested within many circular economy proposals are non-permanent and the captured fossil CO_2 ends up as a net addition of new atmospheric CO_2 after its use in synthetic fuels for example. Whilst it is important that fossil point source CO_2 is captured, stored or reused, it is also crucial to start scaling up atmospheric CO_2 capture now to achieve climate relevant scales in time.

Also it was felt by some stakeholders that the current PtX discussion is advanced in some countries in order to create a positive narrative for fossil CO_2 utilisation (and connected industries) which in most cases ends up in the atmosphere at the end of its use (delayed leakage). It cannot be emphasised strongly enough that CCU and CCS on fossil fuels (in whichever guise) will never replace measures of reducing carbon dioxide emissions but only complement them.

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[119] T. Schaub, R. A. Paciello and M. Limbach, 'Homogeneous catalysis with CO_2 as a building block: an industrial perspective', Applied Homogeneous Catalysis with Organometallic Compounds: A Comprehensive Handbook in Four Volumes, 2017, p. 1601-1614.

[120] The Global CO_2 Initiative, 2018.

[121] G. Nemet et al., 'Negative emissions – Part 3: Innovation and upscaling', Environmental Research Letters, vol. 13, no. 6, 2018, S. 063003.

2.11 Concluding Remarks on CDR Potentials by RDF

According to initial estimates by the authors, this information can be used to estimate the performance of all CO_2 sinks for Switzerland at a total of around 6 million tonnes of CO_2 per year – whereas in the sense of a portfolio idea and an overall balance not all the mentioned conservative assumptions were taken into account. Approaches already tested or applied in Switzerland suggest that the illustrated theoretical potentials are basically attainable. The participating stakeholders have deliberately renounced a comparative presentation of the potentials that can be effectively realised by 2050 in terms of technology and economics. Due to the early stage of the CDR approaches, there are often high uncertainties in such estimations. This is especially true where there are still few scientific publications available. In any case, the identified potentials are likely to be indirectly limited due to available biomass, geological storage potentials, monitorable absorption capacity in soil or storage potential e.g. in cement, social acceptability during storage or transport, available renewable energy or the realisation of new agricultural or forestry practices, and if needed international or cross-national creditability on storage outside of Switzerland. For all approaches, adequate regulation for CDR (carbon pricing) and an almost immediately coordinated expansion of CDR approaches by 2050 and beyond are needed.[122] This, of course, can only be understood in combination with an ambitious mitigation policy in which at least the net zero targets for 2050 are binding.

The following chapter therefore outlines recommended actions to minimise those risks.

[122] *Considering this, it was decided not to make any specific statement of realisable future potentials so as not to leave the impression or encourage communication that CDR was "solved".*

3 Recommended Actions for the Integration of CDR into a Swiss Mitigation Strategy

Current CO_2 prices set by carbon taxes (incentive fee) and/or achieved within the framework of emission trading systems do not reflect the value that climate scientists ascribe to avoided emissions. As long as this is the case both, mitigation efforts and carbon removal technologies will continue to struggle in the rudimentary marketplace.

Switzerland's public authorities, in particular the political and administrative entities have to be aware that they will need to play a leading role and set the tone on matters related to climate mitigation technologies. In addition, owing to the long-term role of climate policy, government and administration will play an important role in relation to CDR. As the externality of CO_2 needs to be priced into the market first, industry can only respond if there are appropriate signals set by a coherent set of regulatory policies, economic trends and commercial opportunities.

The Swiss research and innovation community driving CDR has a very strong sense of purpose to contribute to the "greater good". These thought and innovation leaders are early adopters who – because of CO_2 prices being either too low, or technologies not eligible with current legislation – struggle to identify commercial opportunities."

Still, there is a growing awareness about an ever-increasing body of evidence that there is much higher value to be gained from minimising adverse impacts of climate change against costs of adaptation, mitigation and deployment of CDR. The implementation of adaptation and mitigation measures to offset the hitherto unrecorded rate of climate change are critical first steps. It is also worth bearing in mind that changes or "revolutions" in an economic sector such as the energy sector, usually take decades to have a material impact (e.g. since the early 1980s the growth of the solar PV and wind for power generation has been spectacular but today makes little more than a dent in global energy markets).

Given the absence of commercial drivers, it is clear that NETs require at least time scales of 30-50 years to make a noticeable impact, if conditions are right[123]. Highly innovative countries like Switzerland can enter the vanguard of countries that will drive the inevitable need for NETs. To achieve this the following steps are recommended by the expert participants of this project for urgent consideration.

3.1 CDR is Not a Substitute for Avoiding CO_2 Emissions

Stakeholders agree unanimously that in order to achieve the targets of the Paris Agreement above all else, mitigation that is more aggressive is needed. In other words, CDR is not a substitute for mitigation efforts but needed in addition to full mitigation efforts. This rule needs to be paramount as there are concerns of "moral hazard" insofar as politics could use the existence of atmospheric CDR technologies as an excuse not to place full efforts on mitigation. It is far easier to avoid new CO_2 emissions entering the atmosphere than to remove them.

3.2 Atmospheric CO_2 Removal Required Demands Immediate Scale up of all CDR Approaches

It was stated by a number of stakeholders that urgency to develop CDR technologies to have a material impact is still largely underappreciated by decision shapers and makers. This is backed up

[123] *G. Nemet et al., 'Negative emissions – Part 3: Innovation and upscaling', Environmental Research Letters, vol. 13, no. 6, 2018, S. 063003.*

by a recent seminal three-part review of the scientific literature by the Mercator Research Institute – the largest of its kind so far with over 30.000 sources.[124] The study calls for an annual average of 6 billion tonnes of atmospheric CO_2 removal by 2050 – a target, which would require a scale up rate of close to 60% per annum sustained over three decades. It is worth bearing in mind that these figures are lower than those expected by the IPCC AR5 (2014) which ranged between eight and twelve billion tonnes of annual CO_2 removal to achieve the goals of the Paris Agreement.

Such a scale of growth had been observed for other technologies before, in particular solar PV[125], but is nonetheless extremely challenging. The analysis of Nemet et al.[124] is summarised in Figure 26 and provides an overview of the current state of understanding this challenge. In short, they find that besides research and development and the need for scale-up, almost every other aspect of the innovation stages of CDR is under-researched and that first-hand insights from practitioners are urgently needed for the development of effective incentives. Furthermore, coordinated efforts and governance on the national level is needed urgently to bring CDR to the required scales in time.

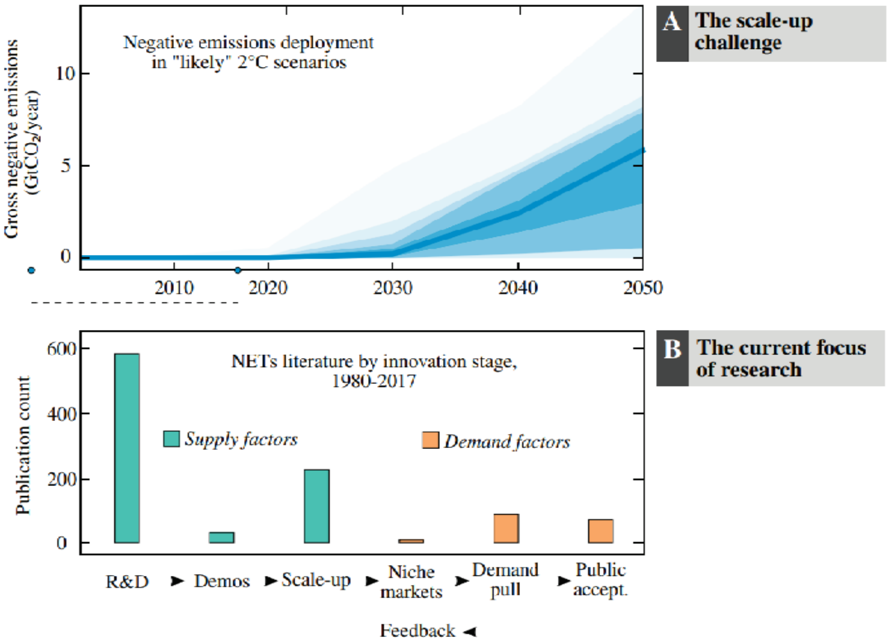

Figure 26: Understanding the scale-up challenge.[124]

Delays in scale-up will lead to higher and therefore harder to meet scale up pathways. It is therefore important to start scaling-up as soon as possible: technical risks are sufficiently well understood and paths to commerciality identified. For Switzerland CDR scale-up pathways need to be developed. These will depend on mitigation pathways and the timeframe in which Switzerland commits to net zero emissions. It is therefore also of great importance to commit as a necessary pre-cursor to a zero emissions pathway in Swiss climate policy. Stakeholders suggest to base this pathway at least on current recommendations of net zero emissions by 2050 for example by the IPCC SR15 or the EU[126] but would welcome the consideration of more ambitious GHG reduction pathways.

In any case a target of net zero emissions by 2050 will determine the scale of negative emissions needed to offset hard to mitigate emissions and is, of course, paramount for developing any future

[124] *G. Nemet et al., 'Negative emissions – Part 3: Innovation and upscaling', Environmental Research Letters, vol. 13, no. 6, 2018, S. 063003.*

[125] *F. Creutzig, P. Agoston, J. C. Goldschmidt, G. Luderer, G. Nemet and R. C. Pietzcker, 'The under-estimated potential of solar energy to mitigate climate change', Nature Energy, vol. 2, no. 9, 2017, S. 17140.*

[126] *European Comission, '2050 long-term strategy', 2018, https://ec.europa.eu/clima/policies/strategies/2050_en.*

net-negative emissions scenarios for Switzerland. Even if it might be possible for Switzerland to develop these scenarios based entirely on a few CDR approaches, such as afforestation or improved soil and agricultural management it is recommended to include both natural and technological approaches discussed above in the pathways for at least three reasons. Firstly, a wider portfolio of CDR approaches will substantially lower risks if some of the approaches or technologies should not deliver as well as foreseen. In addition, only the application of several CDR technologies in parallel can ensure CDR readiness with the required speed. Then if a future CDR portfolio would rely heavily on a set of technology that require for example natural resources (e.g. BECCS – arable land and water) CDR would not develop at scale due to resource constraints. Secondly, as shown, technological approaches to CDR will need to become an extremely large industry to become climate relevant. Being at the forefront of this development will result in sustainable domestic economic growth and allow for exports of the respective technology and know-how developed. Thirdly, solutions like improved soil management are limited to a couple of decades in terms of their effectiveness in delivering negative emissions as the soils saturate over time.

3.3 Sociopolitical Framework and Societal Dialogue

Stakeholders agree unanimously and in accordance with the earlier science dialogue[127] that the issues surrounding mitigation and CDR urgently and swiftly need to be brought to the attention of wider audiences, especially politics and Swiss society. It was widely mentioned that it is important to develop useful narratives in order to effectively communicate these complicated issues. It is therefore recommended to:

- Promote public awareness and dialogue: A social dialogue based on communication and on scientific findings is necessary for the population to make broad-based decisions. This includes highlighting the urgency of the climate crisis and the need for swift implementation of various measures (Thereby considering the main findings of chapters 3.1 and 3.2).
- Use precise language in communication and in any preparation for public debate. Avoid discussion of CDR under generic terms such as geoengineering because they combine two fundamentally different approaches and risk profiles and are thus not effective. The discussion of risks, opportunities, potentials etc. requires a clear definition of each of the approaches.
- Due to sociopolitical sensitivity, a broad stakeholder dialogue at a national level must be proactively tackled and CDR-specific narratives developed that should be included in the active communication of Swiss climate policy (see below).
- Create awareness that CDR has the potential to significantly reduce the cost for other climate change mitigation responses, which potentially is a disproportional relief for weaker social classes.

Societal Dialogue and Narratives

For any societal dialogue useful narratives are important. Participating expert stakeholders confirmed this as an important driver of a public debate. Often it was felt that current narratives are not ideal for climate change in general. In addition, yet there is no overarching narrative for CDR that make this complicated subject easier to grasp. It was suggested that:

Any narrative on CDR should be rooted in a global context (e.g. IPCC scenarios). It is important to include that CDR is mandatory to get to net zero emissions as there will always be residual emissions

[127] White paper of the earlier science dialogue: M. Honegger et al., 'Climate change, negative emissions and solar radiation management: It is time for an open societal conversation. White Paper by Risk Dialogue Foundation St.Gallen for the Swiss Federal Office for the Environment', 2017, www.risiko-dialog.ch/whitepaper.

that need to be mitigated with negative emissions. Eventually CDR can lead to net-negative emissions that will be needed in the second half of this century. To minimize the amount of CDR it is imperative to include that a full effort should be placed on ambitious mitigation (including lifestyle changes). For any useful discussion on mitigation and CDR it is key to translate temperature goals into a fixed Swiss carbon budget that is achieved with a combination of mitigation and CDR, as a discussion purely on temperature goals is likely to remain abstract128.

It was also suggested that it would be better to develop narratives around a “One Ton CO2 Society” rather than the current discussion around the “2000-Watt Society”, as the real issue is not energy consumption, but the carbon intensity of this sector and lifestyles in general. Although a goal like this would need to be formulated in a dynamic way, as CO2 emissions would have to decrease to net zero until 2050.

It was also noted that the current narrative of “going to net zero emissions” was potentially damaging to motivation, as it implicitly renders humans a burden on the planet by their existence alone. It was suggested that a narrative around a “responsible stewardship” where an active careful management by society of emissions and carbon sinks creates the balance prescribed by climate targets and “needed by nature”, might give us a more positive sense of purpose. Here CDR offers a chance to enrich a “responsible stewardship” narrative as CDR approaches can be active means of enlarging carbon sinks.

Furthermore, there is a need to developnarratives that make the different CDR approaches more graspable and place them in the Range of current responses to the climate crisis – namely adaptation and mitigation. This could – given the similarity of CDR to mitigation, especially in a world that is not (yet) gone net-negative – also be discussed under the umbrella term of mitigation. Either as enhanced mitigation or mitigation of hard to mitigate or residual emissions could be useful.

Regarding PtX much of the same applies as for CDR. It was felt that it is important to highlight that – in the same way as a transition to renewable energy or clean tech is currently transforming industry and creating jobs – a transition to CDR and PtX will bring new economic opportunities. These are amplified by the fact that Switzerland is a world leader in some of these technologies.

Therefore, another narrative that was suggested was the relationship between economic growth and climate policy goals. It was suggested that CDR and a circular carbon economy (including PtX) could provide economic growth whilst at the same time contribute to climate goals. With world leaders located in Switzerland, the country could become an innovation leader in the field as a whole.

Lastly a transition to PtX (e.g. solar or e-fuels) will reduce Switzerland's reliance on energy imports, enhance energy supply security. It will also reduce vulnerability to volatile prices of fossil fuels. As with the transition to renewable electricity, a PtX transition will reduce air pollution as e-fuels burn very much cleaner than fossil fuels, creating large economic benefits for human health, economic activity and the environment. Furthermore, in the case of synthetic fuels and materials (PtX) also lead to greater independence of Switzerland from fossil resources.

3.4 Regulation and Supervision

In general, regulation will require differentiated consideration of impacts of different technologies as well as social and economic factors in order to effectively reduce regulatory and institutional barriers. In this context LCAs are of special importance to ensure the positive effect of permanent removal of CO_2 from the atmosphere or prevent additional fossil CO_2 entering the air. It is especially important to focus on adequate systems boundaries covering the whole life cycle of the applied technology

[128] *O. Geden, 'Targeting net zero emissions: A new focus for a more effective climate policy', Kleinman Center for Energy Policy, 2019.*

and of consumed goods and services, ideally “cradle to cradle” for PtX or “cradle to grave” methodologies for CDR.“Cradle to gate” methodologies are to be avoided especially in contexts where CO_2 from point sources (flue gas capture) is allowed as feedstock for PtX or CDR.

Actual CDR must be independently verified through the development of monitoring, reporting and Verification (MRV) measures; one of the major challenges of using CDR is monitoring the permanence of CO_2 storage, especially for natural storage (wood products and soil). Great advances in the operationalisation of MMV measures have been achieved in the field of geological CO_2 storage. Methodical approaches that are pragmatic and practicable have to be created.

Each of the technologies will have to be subject to a demonstration and verification of its sustainability criteria. For example, proof of the sustainable development of biomass in order to exploit the potential of BECCS and biochar will be required in order to avoid competition with food crops. In land-based CDR options, the deployment can have biophysical implications beyond CO_2 removal that require consideration.

3.5 Recommendations for Swiss Climate Policy

In concrete terms, Switzerland’s climate policy needs to incorporate and promote CDR technologies and set an appropriate framework using a three-pronged approach:

1. Continue to increase action in mitigation efforts

- Ambitious mitigation efforts are and will remain the key to a successful climate policy: In line with the evidence brought forward by the climate science community, the IPCC, as well as the Paris Agreement Switzerland should reduce its GHG emissions to net zero by 2050 at the latest. Against this background, the strong emphasis on mitigation must to be complemented by a rapid take-up of CDR approaches. The lattes requires the development of pathways to scale-up and their implementation with a strong sense of urgency.
- CO_2 tax / incentive tax on GHG emissions from fossil sources need to be sufficiently high to trigger an economic and commercial incentive to scale up a broad range of CDR technologies, especially the technical that still require development to bring down their price and thus not pick any winners (none are losers because any and all technologies will be required). We recommend at least 180 CHF per tonne.

2. Support the development of CDR approaches and technologies

Government funding for research and innovation, market introduction, scaling and market diffusion should be allocated sooner than later – even in the CO_2-Act for the 2020s that is currently (2019) in parliament. Waiting for post-2030 is falling into the trap of the moral hazard described in chapter 3.2 Hence society cannot afford to wait.

Historically, CCS research (including DAC) has been recorded in the energy research statistics of the Swiss Federal Office of Energy (SFOE). Until recently, this type of research was developed under an energy technology narrative, and an average around 5 million CHF per year (2015-2018) was invested for R&D as well as in pilot and demonstration projects. In the meantime however, the SFOE and FOEN as well as other Federal Offices (e.g. swisstopo) recognise that carbon capture, utilisation and research relates more to climate change research.[129] [130]

Switzerland's research and innovation in CDR technologies needs to be focused and channeled through, for example a National Competence Center for Research (NCCR) to pursue long-term research on CDR owing to their strategic importance for complying with the Paris Agreement. Whereas the NCCR's book "Climate Variability, Predictability and Climate Risks" (2001-2013) had focused on research in: past climate (variability, trends and extreme events); future climate (processes and forecasting); impacts of climate variability and change and risk assessment (risk hedging and socio-economic response) the time has now come to focus on Switzerland's research and innovation skills on mitigation and negative emission technologies. An NCCR on CDR will provide the scientific and engineering foundation for Switzerland to develop a plethora of new, early-stage technologies and technologically more advanced and ready solutions that can be piloted and demonstrated in the market place.

Stakeholders see the need not only for a national research program (NRP) for solving immediate issues around mature CDR approaches, but, importantly, a much more sustained, long-term and integrated effort that organises Switzerland's overall CDR research capabilities in a much more profound and comprehensive manner. An established NCCR mechanism will also trigger bottom-up initiatives for novel research projects. Allocation of financial resources for those are best served by already established funding mechanisms such as the Swiss National Science Foundation.

Therefore, the Federal Offices should allocate significantly more focus on supporting oriented research on behalf of the Federal Government to provide answers to questions on how Switzerland's climate policy past 2030 can be translated into action, as well as focus on piloting and demonstrating CDR technologies.

The primary agents for coordinated federal government research are the FOEN, FOE and Agroscope, as well as swisstopo (for permanent geological storage).The legal basis for undertaking directed federal research on CDR exists by way of relevant articles in the CO_2-, Energy- and agricultural acts. Thus, it is merely a question of allocating appropriate resources to fund and manage such directed research in support of Switzerland's climate policy. Evidence-based results from this kind of directed research will underpin necessary and informed policy development in such a way that least-cost pathways can be developed. Allowing research and project development of a broad range of CDR technologies in parallel is essential to ensure rapid progress. In all likelihood and common to all technologies where there is not a strong, simple and clear business case, the federal and cantonal governments will have to subsidise prototyping, piloting and demonstrations and reduce other non-financial and regulatory barriers.

Switzerland's industry is expected to undertake science-based innovation, which will be supported by Switzerland's innovation promotion agency, Innosuisse. Naturally, the industry needs to identify and pursue credible pathways to commerciality, driven by a set of corresponding drivers (interest in the marketplace, willingness to pay a price for abating, offsetting and removing GHG emissions, availability of technologies ready for market diffusion, and so on). Where and when needed, Innosuisse is expected to play a leading role by putting appropriate emphasis and priority on supporting industry-led innovation of CDR technologies.

Financing of the technology development within today's highly deficient carbon and greenhouse markets, poses a major challenge. Government and legislators need to realise that to limit warming to 1.5 °C; financial resources must be made available to allow for rapid CDR deployment, diffusion

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[129] *SFOE, 'Energy statistics', 2019, www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken.html. (See heading Energy Research Statistics for annual data, and therein Table 5a for investments into research and development and Table 5b for investments in pilot and demonstration projects).*

[130] *FOEN, 'Innovation landscape: Overview of the national and international funding instruments', 2018, www.bafu.admin.ch/bafu/de/home/themen/bildung/umweltforschung/innovationslandschaft-umwelt-energie.html#region=0&type=1.*

and scale-up. FOEN is encouraged to explore how the legal framework (e.g CO_2 act and the ordinances) need to be adapted so that instruments such as the Technology Fund, the KliK Foundation, support for R&D as well as piloting and demonstration etc. are easily identifiable as vehicles to support CDR technologies. With any support of CDR compliance with SDGs should be considered. Finally, to aid market diffusion the federal and cantonal governments may provide reimbursable investment grants for CDR projects – similar to those that are available for renewable energy projects.

3. Include CDR in Switzerland as an important pillar of Swiss climate policy.

It is strongly recommended that the federal government and the federal administration communicate publically that CDR is essential for fulfilling Switzerland's commitment to the Paris Agreement. The public recognition will serve as the basis to include CDR as an essential (sine-qua-non) pillar of Switzerland's climate policy.

In order to include CDR in Switzerland's climate policy a number of framework conditions needs to be put in place:

- Credibility: CDR approaches need to be explicitly included in the CO_2 act and thus become credible as a viable mechanism to fulfil Switzerland's emissions targets. An explicit mention will ease the support of implementing CDR technologies and projects: funding through compensation mechanisms, for example, can greatly aid market diffusion and scale-up of marketable technologies. Once the value of CO_2 removed from the atmosphere will be recognised, compensation mechanisms for CO_2 neutrality can be reduced progressively in 2050. A long-term view will ease the transfer of economic risks to the market and help create a regulatory framework that incentivises actors to take economic and commercial risks inherent in CDR technologies.
- Create a legal basis and regulatory frameworks for the different types of CDR projects.
- Create a legal basis for negative emissions accounting. Consider the applicability of a CO_2 "price" for negative emissions. This will reduce market distortion and allocate subsidies at the actual cost of technology. Negative emissions accounting when applied to novel technologies poses a number of challenges in terms of auditable accounting rules.
- Apply a risk-based approach in accounting of negative emissions: As long as a technology is applied in small scale, the uncertainties should accepted to be higher.
- Shadow carbon prices (as high as they are needed in 2050) could be applied to legislative impact assessments, infrastructure planning, public procurement, Swiss project funding, and the setting of regulatory benchmarks for sustainable private-sector financing.
- To ensure policy alignment and avoid unintended counter effects, Switzerland's climate policy with respect to CDR needs to be developed in alignment with policies related to agriculture, energy, spatial planning, transport policy (possibly via the Interdepartmental Committee IDA Climate and other ad-hoc working groups on, for example, the underground to manage subsurface CO_2 storage). Examples of the need for policy alignment are wood stocks vs. usage of wood for energy production; biochar as a fuel versus a CDR technology; meeting CO_2 reduction goals across sectors of the economy; encouraging mitigation first, only then CDR technologies and so on.
- Cantonal climate policies and regulations must be aligned with a climate policy that targets net zero emissions by 2050.
- Governance of CDR is important. Switzerland should support international treaties, conventions and protocols that include and enable CDR technologies. Support use for adequate CO_2 pricing. This can happen on all levels: CO_2 taxes, CO_2 levies and emissions trading system.
- Aid the creation of the foundations for CDR in article 6 of the Paris Rulebook. In general, the question of international CO_2 creditability is important. Switzerland should commit itself to and support clear guidelines on an international (UN) level.

4 About the Stakeholder Dialogue

This report is the result of a stakeholder dialogue project on atmospheric carbon dioxide removal (CDR), which the Risk Dialogue Foundation (RDF) conducted between March 2018 and May 2019. The project was built on a dialogue project with leading scientists in the field which was concluded in 2017[131]. For this project more than 25 stakeholders from different NGOs, government agencies, sciences, industries as well as politics took part in this project, which was commissioned by the Federal Office of the Environment (FOEN).

4.1 Focus

In response to the climate crisis, a majority of climate science community proposes a set of actions covering mitigation, adaptation and now also CDR. Some scientists currently wish to investigate yet another set of possible methods to address climate crisis. These are often collectively referred to as either solar radiation modification, solar radiation management (SRM) or occasionally as solar geoengineering. In essence, SRM seeks to reduce the amount of sunlight incident on the Earth and thus reduce global warming. Such methods include the increase of planetary albedo, for example by using stratospheric sulfate aerosols. Some key advantages are thought to be the high speed of deployment and short time required to become fully active, a potentially low investment cost, and the reversibility of their direct climatic effects. However, these approaches also come with a set of known and unknown risks. While there is general awareness of SRM, a lack of detailed knowledge amongst the participants of the project caused stakeholders – unlike initially indented[132] not to include SRM in this report. In General, they advocated that more research needed to be pursued on the subject, and the body of knowledge expanded before systematic technological actions via pilot projects were to be undertaken.

The aim of the project therefore was to identify Switzerland based stakeholders with expertise in CDR or representing those affected by it in order to identify opportunities and risks around CDR with a focus on Switzerland. Further goals of the project included the assembly of important non-science stakeholders and the formation of a Swiss CDR community; the capture of Switzerland's knowledge base on CDR beyond the scientific community; and to draw attention to this important topic so Switzerland's policy makers and informed members of society become aware.

A major insight was that knowledge on the topic is heterogeneous and widely dispersed amongst stakeholders from the different backgrounds meaning that there are "islands" of relevant expertise on integrating mitigation and CDR for the benefit of implementing Switzerland's climate policy and reaching its goals. RDF made use of the dispersed knowledge base to deepen the understanding of many aspects related to governance, communications, and scale up around CDR with this report.

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[131]Final report accessible here: M. Honegger et al., 'Climate change, negative emissions and solar radiation management: It is time for an open societal conversation. White Paper by Risk Dialogue Foundation St.Gallen for the Swiss Federal Office for the Environment', 2017, www.risiko-dialog.ch/whitepaper.

[132] The initial project offer to the FOEN was designed to carefully assess SRM as well.

4.2 Design and Methodology

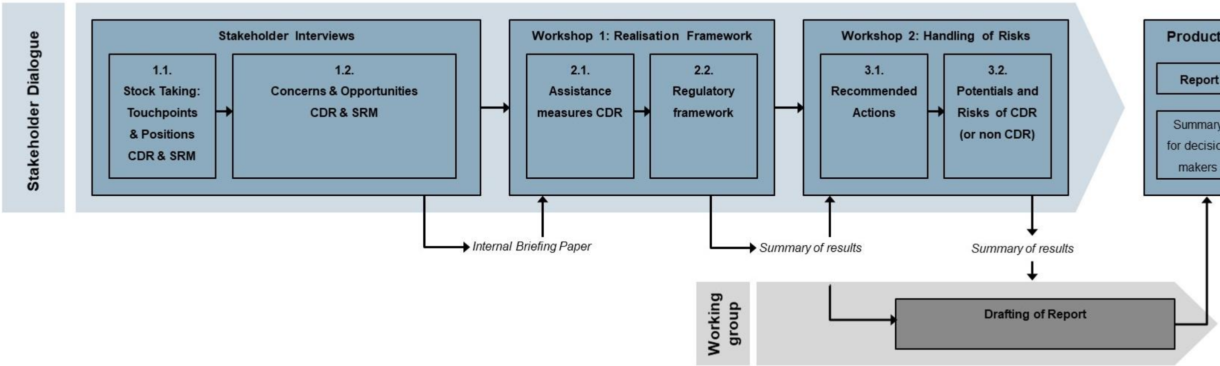

Figure 27. Stakeholder dialogue process for the project.[133]

The process of the stakeholder dialogue was designed as follows. After the invitation of participants, RDF conducted a series of one-on-one interviews with stakeholders under Chatham House rules to ensure maximum freedom of expression. The insights from the interviews where combined in a briefing paper that was sent to all participants before the first workshop and served as a basis for it.

RDF ran two one-day workshops with all participants in Zurich. The aim was to gain further insights on a future implementation of CDR in Switzerland's climate policy and agree on the specifics as well as the format to be covered in this report. After this, a smaller working group took an active part in writing the report. The report was reviewed and commented on by all participants before publication. During the project, RDF also decided to form a small independent group consisting of former chair of ProClim Prof. emeritus Heinz Gutscher, ETH Prof. Michael Stauffacher and ethicist Dr. Ivo Wallimann-Helmer to advise RDF on the project design and become active in case that any irregularities arise amongst participating stakeholders. This was not the case.

4.3 Selection of Stakeholders

In the preparation phase of the project, RDF – with input from FOEN – drew up an initial list of around 80 relevant stakeholders. The aim was to get the widest possible range of experts on CDR approaches which are active in Switzerland, as well as NGOs active in the fields of climate change, sustainability and nature conservation. In addition stakeholders from federal and cantonal offices where invited as well as interested stakeholders from Swiss politics. The list was complemented with stakeholders from industries whose emissions have a considerably high overall impact, such as the cement industry. In the end approximately 40 stakeholders where invited, of which 25 stakeholders participated actively in the dialogue and contributed to this report.

It is important to point out that this group consisted of many different experts in the field but is by no means a representative selection of all relevant Swiss stakeholders. It is rather an expert group on climate change related issues with some stakeholders being experts in CDR.

Lastly, as expertise and available information amongst participating stakeholders[134] on SRM for Switzerland was deemed insufficient to recommend any action in relation to Switzerland's climate policy,

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[133] *Risk Dialogue Foundation, 2018.*

[134] *Efforts were undertaken by Risk Dialogue Foundation to include expert stakeholders on SRM outside of the scientific realm, but with limited success.*

RDF and the present stakeholder constituency decided not to cover this topic in the project. Consequentially, this report does not deal with SRM other than recommending that – in the spirit of freedom of scientific thought – fundamental research needs to be pursued and, importantly, not prohibited.

Glossary

ACCU	Atmospheric carbon capture and utilisation
BECCS	Bio energy with carbon capture and storage
BECCU	Bio energy with carbon capture and utilisation
C	Carbon
CCS	Carbon capture and storage, a set of technologies to capture CO_2 from a number of sources and to permanently store, on timescales relevant for climate change, the captured CO_2 in an appropriate geological location
CCUS	Carbon capture and utilisation
CDR	(Atmospheric) carbon dioxide removal (synonymous with NETs – Negative Emissions Technologies, an expression which has established itself in conjunction with the Paris Agreement)
CO_2 eq.	Carbon dioxide equivalent
DAC	Direct air capture
DACS	Direct air capture and storage
FOEN	Federal Office for the Environment
FTE	Full time equivalent
GHG	Greenhouse gas
Gt	Gigatonnes = 1 billion tonnes = 1,000 million tonnes
IDA Klima	Interdepartmental Committee Climate (Interdepartementaler Ausschuss Klima)
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	5th Assessment Report of the IPCC
IPCC SR15	An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty
LCA	Life cycle analysis/ Life cycle assessment
MMV	Measuring, monitoring and verification
NCCR	National Competence Center for Research
NDCs	Nationally Determined Contributions
Net-negative	An entity (e.g. country) has an overall negative balance between emissions and sinks
Net zero	Balance between emissions and negative emissions.
NETs	Negative emissions technologies (see CDR)
NGO	Non-governmental organisation
NPO	Non-profit organisation
SFOE	Swiss Federal Office of Energy
SOC	Soil organic carbon

PtX	Power-to-X
PyC	Pyrogenic carbon (content) – mentioned as percentage of the above mentioned SOC
PyCCS	Pyrogenic carbon capture and storage
RDF	Risk Dialogue Foundation
R&D	Research & development
SCNAT	Swiss Academy of Natural Sciences
SCS	Soil carbon sequestration
SDG	Sustainable Development Goals
SRM	Solar radiation management
TRL	Technology readiness level
UNEP	United Nations Environment Programme
UN COP	United Nations Conference of Parties (UN Climate Change Conference)

Reference List

Abiven, S., 'Overviews on fire-derived organic matter: stocks, persistence and impact on yields: Meta study of worldwide research', University Zurich; presented at the 1st round table on biochar at FOEN, 2016.

Akademien der Wissenschaften Schweiz, 'Emissionen rückgängig machen oder die Sonneneinstrahlung beeinflussen: Ist «Geoengineering» sinnvoll, überhaupt machbar und, wenn ja, zu welchem Preis?' Swiss Academies Factsheets, vol. 13, no. 4, 2018, https://naturwissenschaften.ch/service/publications/106135-emissionen-rueckgaengig-machen-oder-die-sonneneinstrahlung-beeinflussen-ist-geoengineering-sinnvoll-ueberhaupt-machbar-und-wenn-ja-zu-welchem-preis, (accessed 15 July 2019).

Alcántara, V., A. Don, R. Well and R. Nieder, 'Deep ploughing increases agricultural soil organic matter stocks', Global Change Biology, vol. 22, no. 8, 2016, p. 2939-2956.

Anderson, K. and G. Peters, 'The trouble with negative emissions: Reliance on negative-emission concepts locks in humankind's carbon addiction', Science, vol. 354, no. 6309, 2016, p.182-183, www.web.cemus.se/wp-content/uploads/2018/02/The-Trouble-with-Negative-Emissions.pdf, (accessed 12 July 2019).

Autret, B., B. Mary, C. Chenu, M. Balabane, C. Girardin, M. Bertrand, G. Grandeau, and N. Beaudoin, 'Alternative arable cropping systems: A key to increase soil organic carbon storage? Results from a 16 year field experiment', Agriculture Ecosystems & Environment, vol. 232, 2016, p. 150-164.

Baker, J.M., T. E. Ochsner, R. T. Venterea, T. J. Griffis, 'Tillage and soil carbon sequestration - What do we really know?', Agriculture, Ecosystems & Environment, 2007, vol. 118, no. 1-4, p. 1-5.

Begert, M. and C. Frei, 'Long-term area-mean temperature series for Switzerland – Combining homogenized station data and high resolution grid data', International Journal of Climatology, vol. 38, no. 6, 2018, pp. 2792-2807, https://doi.org/10.1002/joc.5460.

Blaser, H. and F. Abächerli, 'Verschiedene Erfahrungen in Gesprächen wiedergegeben', Langenbruck, Faoug, Neuheim, 2016/2017/2018.

Boden, T. A., G. Marland and R. J. Andres, 'Global, regional, and national fossil-fuel CO_2 emissions', Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tenn., USA, 2009.

Brändli, U.-B. (Red.), 'Schweizerisches Landesforstinventar. Ergebnisse der dritten Erhebung 2004–2006', Swiss Federal Institute for Forest, Snow and Landscape Research WSL and Federal Office for the Environment FOEN, 2010. p. 312, www.lfi.ch/publikationen/publ/LFI3_Ergebnisbericht.pdf, (accessed 2 June 2019).

Buchkina, N. P., R. Hüppi and J. Leifeld, 'Biochar and short-term N_2O and CO_2 emission from plant residue-amended soil with different fertilisation history', Zemdirbyste-Agriculture, vol. 106, no. 2, 2019, p. 99-106, (peer reviewed 2019).

Bundesamt für Meteorologie und Klimatologie MeteoSchweiz, Temperatur- und Niederschlagsentwicklung,[website], 2019, https://www.meteoschweiz.admin.ch/home/klima/klimawandel-schweiz/temperatur-und-niederschlagsentwicklung.html, (accessed 11 July 2019).

Cabo, M., 'Policy and Technology Challenges for Bio-CCS', Presentation during the EU Sustainable Energy Week, ECN The Netherlands, 2012, https://publicaties.ecn.nl/PdfFetch.aspx?nr=ECN-L--12-041, (accessed 2 July 2019).

Callow, B., I. Falcon-Suarez, S. Ahmed and J. Matter, 'Assessing the carbon sequestration potential of basalt using X-ray micro-CT and rock mechanics', International Journal of Greenhouse Gas Control, vol. 70, 2018, pp.146-156, https://doi.org/10.1016/j.ijggc.2017.12.008, (accessed 2 July 2019).

CarbFix, 2019, www.carbfix.com, (accessed 10 July 2019).

Chen, S., D. Arrouays, D. A. Angers, M. P. Martin, and C. Walter, 'Soil carbon stocks under different land uses and the applicability of the soil carbon saturation concept', Soil and Tillage Research, vol. 188, 2019, p. 53-58.

Chenu, C., D. A. Angers, P. Barré, D. Derrien, D. Arrouays and J. Balesdent, 'Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations', Soil and Tillage Research, vol. 188, 2019, p. 41-52.

Chevalier, G., L. W. Diamond and W. Leu, 'Potential for deep geological sequestration of CO_2 in Switzerland: a first appraisal', Swiss Journal of Geosciences, vol. 103, no. 3, 2010, p. 427-455.

Climeworks, 'Cost target for large scale plants', 2018.

Consoli, C., 'Bioenergy and Carbon Capture and Storage', Global CCS Institute, 2019.

CH2018, 'CH2018 – Climate Scenarios for Switzerland, Technical Report', National Centre for Climate Services, Zurich, 2018, pp. 271, www.nccs.admin.ch/nccs/de/home/klimawandel-und-auswirkungen/schweizer-klimaszenarien/technical-report.html, (accessed 9 July 2019)..

Creutzig, F., P. Agoston, J. C. Goldschmidt, G. Luderer, G. Nemet and R. C. Pietzcker, 'The underestimated potential of solar energy to mitigate climate change', Nature Energy, vol. 2, no. 9, 2017, S. 17140.

European Comission, '2050 long-term strategy', 2018, https://ec.europa.eu/clima/policies/strategies/2050_en, (accessed 10 July 2019).

European Federation for Transport and Environment, 'Roadmap to decarbonizing European aviation', 2018, www.transportenvironment.org/sites/te/files/publications/2018_10_Aviation_decarbonisation_paper_final.pdf, (accessed 20 June 2019).

Fajardy, M. and N. Mac Dowell, 'Can BECCS deliver sustainable and resource efficient negative emissions?', Energy & Environmental Science, vol. 10, no. 6, 2017, p. 1389-1426.

FAO, 2017, www.fao.org/nr/water/aquastat/water_use.

Fichtl, H. and M. Jutz, 'Abschätzungen und teilweise Erhebung, sowie Vergleich mit anderen Quellen von Daten zum Aktivkohle-Import in die Schweiz im Zuge der Einführung der Pflicht zur 4. Klärstufe bei ARA in der Schweiz', Zürich, 2019.

FOEN, 'Innovation landscape: Overview of the national and international funding instruments', 2018, www.bafu.admin.ch/bafu/de/home/themen/bildung/umweltforschung/innovationslandschaft-umwelt-energie.html#region=0&type=1, (accessed 10 July 2019).

FOEN, 'Switzerland's National Inventory Report: GHG Inventory 1990-2017', 2019, www.bafu.admin.ch/dam/bafu/en/dokumente/klima/klima-climatereporting/National_Inventory_Report_CHE.pdf.download.pdf/National_Inventory_Report_CHE_2019.pdf, (accessed 10 May 2019).

Fuss, S., W. F. Lamb, M. W. Callaghan, J. Hilaire, F. Creutzig, T. Amann, T. Beringer, W. de Oliveira Garcia, J. Hartmann, T. Khanna, G. Luderer, G. F. Nemet, J. Rogelj, P. Smith,, J. L. Vicente Vicente, J. Wilcox, M. del Mar Zamora Dominguez and J. C. Minx, 'Negative emissions – Part 2: Costs, potentials and side effects', Environmental Research Letters, vol. 13, no. 6, 2018, 063002.

Gattinger, A. and M. Scheifele, 'The returning N2O effect of biochar in soils', presented at FiBL, Frick, 2016.

Geden, O., 'Targeting net zero emissions: A new focus for a more effective climate policy', Kleinman Center for Energy Policy, 2019, https://kleinmanenergy.upenn.edu/sites/default/files/policydigest/Targeting-Net-Zero-Emissions.pdf, (accessed 10 July 2019).

Glaser, B., L. Haumaier, G. Guggenberger and W. Zech, 'The'Terra Preta'phenomenon: a model for sustainable agriculture in the humid tropics', Naturwissenschaften, vol. 88, no. 1, 2001, p. 37-41.

Government Offices of Sweden, 'Sweden’s carbon tax', 2019, www.government.se/government-policy/taxes-and-tariffs/swedens-carbon-tax/, (accessed 15 July 2019).

Green Car Congress, 'Drax, C-Capture to pilot Europe’s first bioenergy carbon capture storage project', 2018, www.greencarcongress.com/2018/05/20180521-drax.html, (accessed 10 July 2019).

Greenpeace, 'Die CCS-Technologie gaukelt wirksamen Klimaschutz vor', 2008, www.greenpeace.ch/de/story/17690/die-ccs-technologie-gaukelt-wirksamen-klimaschutz-vor, (accessed 21 August 2019).

Grubler, A., C. Wilson, N. Bento, B. Boza-Kiss, V. Krey, D. McCollum, N. D. Rao, K. Riahi, J. Rogelj,S. DeStercke, J. Cullen, S. Frank, O. Fricko, F. Guo, M. Gidden, P. Havlík, D. Huppmann, G. Kiesewetter, P. Rafaj, W. Schoepp, and H. Valin, 'A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies', Nature Energy, vol. 3, no. 6, 2018, p. 515, www.nature.com/articles/s41560-018-0172-6, (accessed 4 July 2019).

Gutknecht, V., S. Ó. Snæbjörnsdóttir, B. Sigfússon, E. S. Aradóttir and L. Charles, 'Creating a carbon dioxide removal solution by combining rapid mineralization of CO_2 with direct air capture', Energy Procedia, vol. 146, 2018, p. 129-134.

Honegger, M., S. Münch, A. Hirsch, C. Beuttler, T. Peter, W. Burns, O. Geden, T.Goeschl, D. Gregorowius, D. Keith, M. Lederer, A. Michaelowa, J. Pasztor, S. Schäfer, S. Seneviratne, A. Stenke, A. Patt, I. Wallimann-Helmer, 'Climate change, negative emissions and solar radiation management: It is time for an open societal conversation. White Paper by Risk Dialogue Foundation St.Gallen for the Swiss Federal Office for the Environment', 2017, www.risiko-dialog.ch/whitepaper, (accessed 5 April 2019).

Honegger, M. and D. Reiner, 'The political economy of negative emissions technologies: consequences for international policy design', Climate Policy, vol. 18, no. 3, 2018, p. 306-321.

Hüppi, R., R. Felber, M. Krauss, J. Six, J. Leifeld and R. Fuß, 'Restricting the nonlinearity parameter in soil greenhouse gas flux calculation for more reliable flux estimates', PloS one, vol. 13, no. 7, 2018, e0200876, (peer reviewed 2018).

IEA, 'Global Energy & CO2 Status Report: The latest trends in energy and emissions in 2018', 2019, www.iea.org/geco/data, (accessed 5 July 2019).

IEAGHG, 'Potential for Biomass and Carbon Dioxide Capture and Storage: Report 2011/06', 2011.

IMO, 'Carbon Capture and Sequestration', 2019, www.imo.org/en/OurWork/Environment/LCLP/EmergingIssues/CCS/Pages/default.aspx, (accessed 10 July 2019).

IPCC AR5, 2014: IPCC, 'Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change' [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 2014, pp. 151, www.ipcc.ch/report/ar5/syr, (accessed 15 July 2019).

IPCC SR15, 2018: IPCC, 'Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty' [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)], World Meteorological Organization, Geneva, Switzerland, 2018, pp. 32, www.ipcc.ch/sr15, (accessed 10 July 2019).

Kammann, C., L. Grünhage, D. Busch, C. Müller, G. Dörger, K. Hanewald and T. Schmid, 'Biokohle: Ein Weg zur dauerhaften Kohlenstoff-Sequestrierung', Hessisches Landesamt für Umwelt und Geologie, 2010, p. 1-8.

Keel, S. G., T. Anken, L. Büchi, A. Chervet, A. Fliessbach, R. Flisch, O. Huguenin-Elie, P. Mäder, J. Mayer, S. Sinaj, W. Sturny, C. Wüst-Galley, U. Zihlmann, and J. Leifeld, 'Loss of soil organic carbon in Swiss long-term agricultural experiments over a wide range of management practices', Agriculture, Ecosystems and Environment, in press.

Keith, D. W., G. Holmes, D. S. Angelo and K. Heidel, 'A Process for Capturing CO2 from the Atmosphere', Joule, vol. 2, no. 8, 2018, p. 1573-1594, www.cell.com/joule/pdf/S2542-4351(18)30225-3.pdf, (accessed 2 June 2019).

Keller, T., R. Hüppi and J. Leifeld, 'Relationship between greenhouse gas emissions and changes in soil gas diffusivity in a field experiment with biochar and lime', Journal of Plant Nutrition and Soil Science, vol. 182, no. 4, 2019, p. 667-675, (peer reviewed 2019).

Kemper, J., 'Biomass and carbon capture and storage – a review', International Journal of Greenhouse Gas Control, vol. 40, 2015, p. 401-430.

Lagerblad, B., 'Carbon dioxide uptake during concrete life cycle: State of the art', Stockholm: Swedish Cement and Concrete Research Institute, 2005.

Lal, R., 'Sequestering carbon in soils of agro-ecosystems', Food Policy, vol. 36, 2011, p.33-39.

Leemann, A. and F. Hunkeler, 'Carbonation of concrete: assessing the CO2-uptake', 2016, www.cemsuisse.ch/cemsuisse/forschung/forschungsberichte/berichte_2016/index.html?lang=de

Leifeld, J., C. Alewell, C. Bader, J. P. Krüger, J. P., C. W. Mueller, M. Sommer, M. Steffens and S. Szidat, 'Pyrogenic carbon contributes substantially to carbon storage in intact and degraded northern peatlands', Land degradation & development, vol. 29, no. 7, 2018, p. 2082-2091, (peer reviewed, 2018).

Limeco, 'Leuchtturmprojekt bei Limeco: Gemeinden sagen Ja zur schweizweit ersten industriellen Power-to-Gas-Anlage', 2018, www.limeco.ch/de/aktuell/pressemitteilungen/leuchtturmprojekt_power-to-gas-anlage, (accessed 10 July 2019).

Luo, Z., E. Wang and O. J. Sun, 'Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments', Agriculture, Ecosystems & Environment, vol. 139, 2010, p. 224-231.

Meier, A. et al., 'Projekt AgroCO2ncept, 26 Landwirtschaftsbetriebe wollen Klimapositiv werden', Flaach, 2016.

Mercator Research Institute (MCC), 'Vorsicht beim Wetten auf Negative Emissionen: Neue Technologien sollen die CO2-Hypothek abbauen – trotz unsicherer Auswirkungen', MCC-Kurzdossier, no.2, 2016, www.mcc-berlin.net/forschung/negativeemissionen.html (accessed 10 July 2019).

Michaelowa, A., M. Allen, and F. Sha, 'Policy instruments for limiting global temperature rise to 1.5° C – can humanity rise to the challenge?', 2018, pp. 275-286.

Ministry of the Environment, Energy and the Sea (MEEM), 'Le prix du carbone: Levier de la transition énergetique', 2016, www.ecologique-solidaire.gouv.fr/sites/default/files/prix-carbone_4p_DEF_Fr.pdf, (accessed 10 July 2019).

Minx, J. C., W. F. Lamb, M. W. Callaghan, S. Fuss, J. Hilaire, F. Creutzig, T. Amann, T. Beringer, W. de Oliveira Garcia, J. Hartmann, T. Khanna, D. Lenzi, G. Luderer, G. F. Nemet, J. Rogelj, P. Smith, J. L. Vicente Vicente, J. Wilcox, and M. del Mar Zamora Dominguez, 'Negative emissions—Part 1: Research landscape and synthesis', Environmental Research Letters, vol. 13, no. 6, 2018, p. 063001, https://iopscience.iop.org/article/10.1088/1748-9326/aabf9b, (accessed 10 July 2019).

National Academies of Sciences, Engineering, and Medicine, 'Negative Emissions Technologies and Reliable Sequestration: A Research Agenda', Washington, DC: The National Academies Press, 2019, https://doi.org/10.17226/25259, (accessed 2 June 2019).

Nemet, G. F., M. W. Callaghan, F. Creutzig, S. Fuss, J. Hartmann, J. Hilaire, W.F. Lamb, J.C. Minx, S. Rogers und P. Smith, 'Negative emissions – Part 3: Innovation and upscaling', Environmental Research Letters, vol. 13, no. 6, 2018, S. 063003.

Peters, G., 'Stylised pathways to «well below 2°C»', 2018, https://energiogklima.no/blogg/stylised-pathways-to-well-below-2c, (accessed 5 March 2019).

Postic, S. and C. Métivier, 'Global Carbon Account 2019', Institute for Climate Economics (I4CE), 2019, www.i4ce.org/download/global-carbon-account-2019, (accessed 5 August 2019).

Realmonte, G., L. Drouet, A. Gambhir, J. Glynn, A. Hawkes, A. C. Köberle and M. Tavoni, 'An inter-model assessment of the role of direct air capture in deep mitigation pathways', Nature communications, vol. 10, no. 1, 2019, p. 3277, www.nature.com/articles/s41467-019-10842-5, (accessed 15 August 2019).

Reisser, M., R. S. Purves, M. W. Schmidt and S. Abiven, 'Pyrogenic carbon in soils: a literature-based inventory and a global estimation of its content in soil organic carbon and stocks', Frontiers in Earth Science, vol. 4, no. 80, 2016.

SCCER-SoE, 'ELEGANCY: CO2 storage project in Mont Terri', 2019, www.sccer-soe.ch/research/pilots-demos/elegancy.

Schaub, T., R. A. Paciello and M. Limbach, 'Homogeneous catalysis with CO 2 as a building block: an industrial perspective', Applied Homogeneous Catalysis with Organometallic Compounds: A Comprehensive Handbook in Four Volumes, 2017, p. 1601-1614.

Schiedung, M., C.S. Tregurtha, M. H. Beare, S.M. Thomas and A. Don, 'Deep soil flipping increases carbon stocks of New Zealand grasslands', Global Change Biology, 2019, p. 1-14.

Schimmelpfennig, S., C. Müller, L. Grünhage, C. Koch and C. Kammann, 'Biochar, hydrochar and uncarbonized feedstock application to permanent grassland – Effects on greenhouse gas emissions and plant growth', Agriculture, Ecosystems & Environment, vol. 191, 2014, p. 39-52.

Schmid, M., 'Interviews of 6 biochar importers, producers and traders and 3 feeding additive producers and traders in Switzerland', Market analysis for customers in ZH and TG, Langenbruck, 2019, unpublished.

Schmidt, H.P., 'Certification and trading of carbon sinks from biomass and biochar', Ithaka Institute, Switzerland, 2019.

Schwaab, J., M. Bavay, E. Davin, F. Hagedorn, F. Hüsler, M. Lehning, M. Schneebeli, E. Thürig, and P. Bebi, 'Carbon storage versus albedo change: radiative forcing of forest expansion in temperate mountainous regions of Switzerland' Biogeosciences, vol. 12, no. 2, 2015, p. 467-487, https://boris.unibe.ch/62981/1/bg-12-467-2015.pdf, (accessed 2 July 2019).

Seitler, E., 'Reduktion von NH_3-Emissionen aus Mist mittels Pflanzenkohle sowie Methodenentwicklung für Ammoniakmessung im Stall', Master Thesis, FHNW, 2015.

SFOE, 'Energy statistics', 2019, www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken.html, (accessed 10 July 2019).

Smith, P., S. J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, E. Kato, R. B. Jackson, A. Cowie, E. Kriegler, D. P. van Vuuren, J. Rogelj, P. Ciais, J. Milne, J. G. Canadell, D. McCollum, G. Peters, R. Andrew, V. Krey, G. Shrestha, P. Friedlingstein, T. Gasser, A. Grüblero, W. K. Heidug, M. Jonas, C. D. Jones, F. Kraxner, E. Littleton, J. Lowe, J. R. Moreira, N. Nakicenovic, M. Obersteiner, A. Patwardhan, M. Rogner, E. Rubin, A. Sharifi, A. Torvanger, Y. Yamagata, J. Edmonds, and C. Yongsung, 'Biophysical and economic limits to negative CO_2 emissions', Nature climate change, vol. 6, no. 1, 2016, p. 42-5, https://core.ac.uk/download/pdf/77052341.pdf, (accessed 15 July 2019).

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko, M. Howden, T. McAllister, G. Pan, V. Romanenkov, U. Schneider, S. Towprayoon, M. Wattenbach, and J. Smith, 'Greenhouse gas mitigation in agriculture'. Philosophical Transactions of the Royal Society B: Biological Sciences, vol. 363, no. 1492, 2008, p. 789-813, www.ncbi.nlm.nih.gov/pmc/articles/PMC2610110/pdf/rstb20072184.pdf, (accessed 13 July 2019).

Stripple, H., C. Ljungkrantz, T. Gustafsson and R. Andersson, 'CO_2 uptake in cement-containing products: Background and calculation models for IPCC implementation', Commissioned by Cementa AB and IVL research foundation, 2018, https://cembureau.eu/media/1753/ivl-report-co2-uptake-in-cement-containing-products-isbn-number-b2309.pdf, (accessed 20 July 2019).

The Global CO_2 Initiative, 2018.

The Royal Society and Royal Academy of Engineering, 'Greenhouse gas removal', 2018, https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf, (accessed 5 May 2019).

Thees, O., V. Burg, M. Erni, G. Bowman und R. Lemm, 'Biomassenpotenziale der Schweiz für die energetische Nutzung', Ergebnisse des Schweizerischen Energiekompetenzzentrums SCCER BIOSWEET, WSL Bericht, no. 57, 2017, p. 299, http://holzenergie-nws.ch/wp-content/uploads/2018/02/biomassenpotenziale-der-schweiz-wsl-berichte-heft-57-2017.pdf, (accessed 15 July 2019).

Thürig, E. and B. Traub, 'Non-forest areas converted to forest: standing stock, gains and losses in biomass', Report commissioned by the Swiss Federal Office for the Environment, Bern, 2015, www.bafu.admin.ch/dam/bafu/en/dokumente/klima/klima-climatereporting-referenzen-cp2/thuerig_e_traub_b2015.pdf.download.pdf/thuerig_e_traub_b2015.pdf, (accessed 15 July 2019).

UNEP, 'The Emissions Gap Report 2018', 2018, www.unenvironment.org/resources/emissions-gap-report-2018

UNFCCC, 'Paris Agreement', 2015, https://unfccc.int/sites/default/files/english_paris_agreement.pdf, (accessed 10 July 2019).

Werner, F., R. Taverna, P. Hofer, E. Thürig, and E. Kaufmann, E., National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. Environmental Science & Policy, vol. 13, no. 1, 2010, p. 72-85.

World Meteorological Organization, 2019

World Resource Institute, Half a Degree of Warming makes a big Difference: Explaining IPCC's 1.5°C Special Report, 2018, www.wri.org/blog/2018/10/8-things-you-need-know-about-ipcc-15-c-report, (accessed 15 July 2019).

WWF, 'Marktananlyse Holzkohle 2018: Wir grillieren den Tropenwald', 2018, www.wwf.ch/sites/default/files/doc-2018-09/Bericht_Holzkohle.pdf, (accessed 10 July 2019).