DeCIRRA

FINAL SYNTHESIS REPORT:

INCENTIVES AND FRAMEWORK CONDITIONS FOR CARBON MANAGEMENT IN SWITZERLAND

DeCIRRA Subproject 3, Deliverable 3.4

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Executive Summary

The project and its context. This report synthesises the findings of sub-project 3 (SP3) of the Innosuisse flagship project DeCIRRA (Decarbonisation of Cities and Regions with Renewable Gases). Article 3 of the Swiss Climate and Innovation Act (KIG) requires net-zero greenhouse gas emissions by 2050, with negative emission technologies reserved for emissions that cannot otherwise be avoided. On the basis of the Energy Perspectives 2050+, the Federal Council estimates that Switzerland will need around 7 Mt CO_2 of removals per year – 2 Mt domestically and 5 Mt abroad – plus a further 5 Mt of capture and storage as emission reductions. While the other DeCIRRA sub-projects are technical in nature, SP3 is interdisciplinary and adds an economic and social-science perspective, covering both technical carbon capture, utilisation and storage (CCUS) and biological removal approaches: timber carbon capture and storage (TCCS), bioenergy with carbon capture and storage (BECCS), biochar and hydrochar, and direct air carbon capture and storage (DACCS), together with the CO_2 transport and storage infrastructure on which the gaseous options depend. Beyond research, SP3 established expert groups of key actors in Swiss defossilisation to disseminate knowledge and support faster scaling.

How the work proceeded. SP3 was structured over four and a half years. In the first phase, the project team reviewed the literature, assessed existing Swiss projects and the carbon management approaches (CMAs) relevant for Switzerland, mapped the important actors and established the expert groups. In the second phase, it analysed current carbon management projects and surveyed stakeholders on their roles, cooperation, importance and attitudes. In the third phase, it produced a scenario report analysing pathways to net zero with an energy system model, including the policies needed for implementation (Guidati et al. 2024). In the final phase, it conducted a representative public survey on the perception of CO_2 transport options, assessed the wider economic consequences of the net-zero target across scenarios using a computable general equilibrium model, and analysed business models on the basis of a literature review and interviews.

What is new relative to the first synthesis report. This final report is not a restatement of the 2023 synthesis. It integrates updated results from the modelling of CMA use under four scenarios for Swiss decarbonisation by 2050 (Octopus, Butterfly, Clam and Snail). Compared to the scenario report, the modelling has been updated with revised costs and potentials, hydrochar, capture at pyrolysis plants, seasonal resolution in the electricity sector, supply security constraints and explicit modelling of sustainable fuels, and the energy system model is now coupled with a computable general equilibrium model to capture macroeconomic and distributional effects. Two empirical components are new: a representative survey on public perception of CO_2 transport and storage (3,058 respondents from German-speaking Switzerland, November 2025) and a business model analysis across all four CMAs . The policy landscape has also moved quickly. In Switzerland, the revised CO_2 Act and the Climate and Innovation Act entered into force in January 2025, the KIG's CHF 1.2 billion programme is operational, a CCS framework act is due for consultation by the end of 2026, and cross-border storage is enabled by the London Protocol export amendment and bilateral agreements with Norway and other countries. Internationally, the EU adopted its first Delegated Regulation 2026/285 on certification methodologies for permanent carbon removals activities and removals standards were agreed under Article 6.4.

Two options are robust across all futures (see Figure A). Timber in construction is the first-priority approach in every scenario, reaching its maximum modelled potential of about 2 Mt CO_2 per year. Biochar is likewise always part of the optimal mix, between 1.66 Mt CO_2/year (Butterfly) and 2.58 Mt CO_2/year (Snail), while hydrochar enters only in Clam and Snail at around 1 Mt CO_2/year, because its storage must be paid for whereas biochar can earn revenue. Together with CO_2 capture at biogas plants, these form a no-regret cluster: available today, at TRL 9, independent of CO_2 infrastructure, and constrained by regulatory gaps rather than technological immaturity. Domestic DAC, by contrast, is not part of the optimal mix in any updated scenario: allocating scarce low-carbon electricity to DAC is not cost-efficient, and domestic storage is limited. Switzerland's role lies in the technology value chain rather than in domestic deployment.

Infrastructure is the decisive variable. Where international offsets are unavailable, capture at large point sources – waste incineration, cement, chemicals – becomes dominant, with CO_2 stored abroad. Marginal abatement costs mirror the assumed infrastructure costs closely: marginal abatement costs reach around CHF 220/tCO_2e in Butterfly, where CO_2 transport and storage are cheap, against CHF 1,500/tCO_2e in Clam, where those costs were assumed to be prohibitive as cooperation with the EU fails in order to show what that would change. At the latter cost level, achieving the net-zero target is unlikely to command sufficient political and public support. Because neither capture operators nor infrastructure providers are willing to invest first, the federal government is the indispensable coordinator.

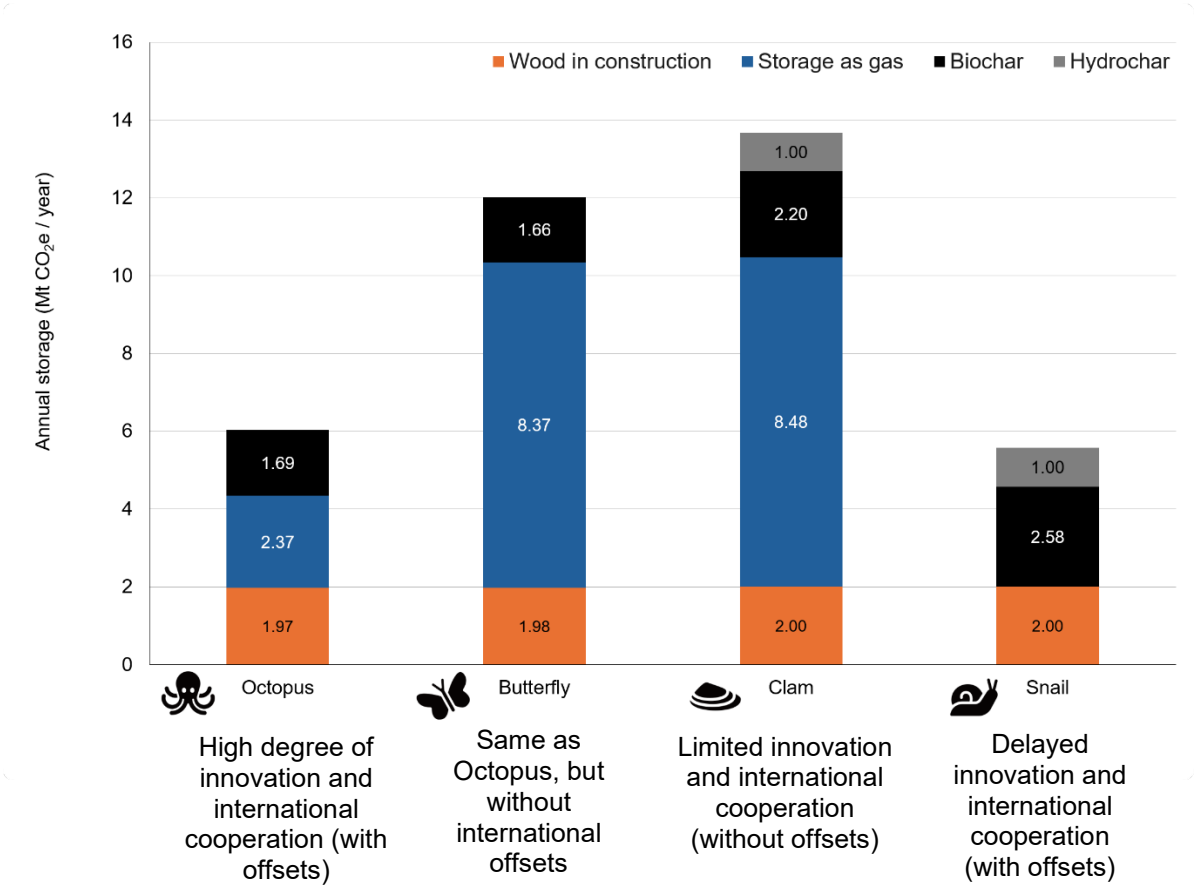


Figure A: Optimal composition of CO_2 storage types in 2050 under the four scenarios

Economic costs exceed energy-system costs. The Butterfly and Octopus scenarios share technology assumptions; they differ only in whether the last 6 Mt are abated domestically (Butterfly) or bought abroad at the same marginal cost (Octopus). General equilibrium takes into account that purchasing offsets abroad worsens Switzerland's terms of trade, making welfare losses about 25 % higher under Octopus than Butterfly. For offsets to be welfare-optimal they would need to be some 36 % cheaper than domestic abatement, which seems difficult as high quality and environmental integrity offsets will be more costly. Delay is more damaging still: Snail's welfare cost is more than 2.5 times Butterfly's. An active strategy combining innovation, international cooperation and domestic abatement is the most favourable of the four scenarios.

Regulation, not technology, creates the market. Across all CMAs no commercial business case exists without regulatory intervention, since removal is a public good whose value must be assigned by policy. The analysis identifies a triple market failure today: minimal integration into compliance markets, missing transport and storage infrastructure, and absent certification standards for some approaches. Adoption today rests on co-benefits – notably biochar sales – and on the voluntary market. A survey of some 140 stakeholders across four actor groups (major point-source emitters, suppliers of removal technologies and services, regulators, and supporting service providers) found broad consensus that a CO_2 price is the key instrument, followed by binding targets favoured particularly by regulators. FOEN and SFOE were seen as the most important actors, followed by waste incineration plants, the Federal Institutes of Technology and politicians; the cement industry is important but less well integrated. Four measures follow for market formation: public procurement of certified Swiss removal services as an immediate demand stimulus, reinstatement of the SFOE demonstration programme with dedicated funding streams, redesign of KIG support to give early-stage projects low-threshold pilot opportunities, and Carbon Contracts for Difference as a risk-sharing scaling instrument which can fill the gap between current carbon prices and needed prices for the more costly CMAs.

Accounting and certification for timber storage in construction remains unresolved. Life cycle assessment, national inventory accounting and project-level carbon market accounting are frequently conflated and must be kept separate. The central contested issue is that fossil CO_2 warms the atmosphere for millennia while most available approaches based on biomass store carbon for far shorter periods. Switzerland's 30-year permanence requirement is internationally out of step. For TCCS, the report compares the HWP-pool approach behind the "Senke Schweizer Holz" scheme with project-level

and value-chain alternatives. A structured comparison of the options taking account international developments is needed in time for the 2030 revision of Swiss climate policy. It is clear that demand should not come from the transport sector, as it does not count among the hard-to-abate emissions. In addition, the current Swiss permanence requirement of 30 years is not compatible with international standards. The option of using TCCS to compensate for short-lived greenhouse gases such as methane should therefore be examined.

Public acceptance is higher than commonly assumed, but uneven. Across all six transport options tested in the representative survey, around 88 % of respondents were neutral or supportive and only about 12 % opposed (see Figure B). Repurposed pipelines are significantly better accepted than new construction, and informing respondents that CO_2 is already transported in Switzerland for industrial purposes raised support across every transport option. This suggests that greater communication effort is needed, in particular by actively informing the public about the CO_2 transport that already takes place.

Opposition correlates with age, lower climate concern and lower trust rather than with income or region. Storage is the weak point: 60 % feel uncomfortable with geological CO_2 injection against about 26 % for solid biochar stored underground, although 73 % support domestic geological storage in principle if it can be done safely – a challenge of trust-building rather than fundamental opposition.

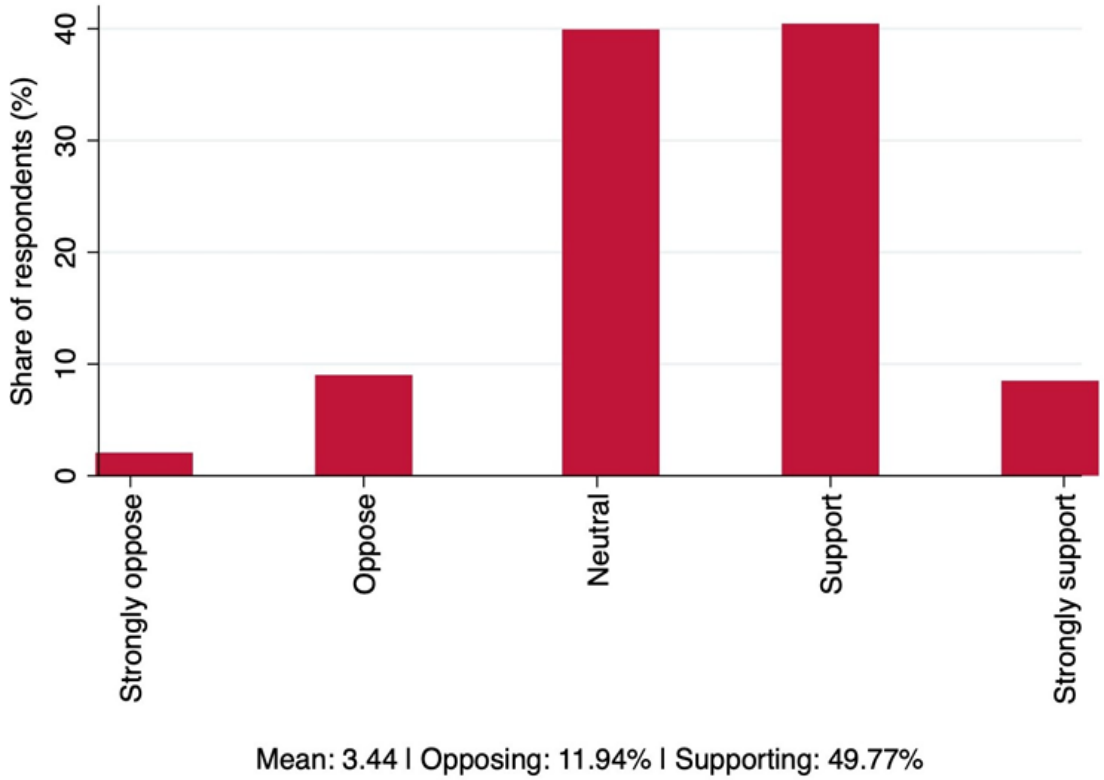


Figure B: Frequency across all six transport options: ‘’To what extent do you support this potential transport route to a permanent CO_2 storage site?”

Distributional design matters. Command-and-control regulation has a progressive incidence in every scenario, whereas financing CCS at waste incineration plants through household waste fees is regressive and risks incentivising illegal dumping. Extending the advance recycling contribution to producers and importers of plastic packaging could be analysed as an alternative, placing the carbon cost at market entry, where material choices are made and the potential for substitution is greatest.

Priorities. Secure early access to European CO_2 storage while developing domestic capacity; establish stable, internationally compatible investment frameworks as the largest available cost-reduction lever; remove the regulatory barriers to biochar and hydrochar; prefer domestic reductions and removals over expensive offsets. Detailed policy recommendations are set out in the final Section 6. Remaining research needs include regionally resolved modelling of infrastructure pathways, long-term Swiss data on biochar permanence and soil effects, quantification and integration options for co-benefits and external costs, accounting and incentive schemes for TCCS, detailed analysis on recycling contribution by producers and importers of plastic packaging for waste incineration plants and the design of liability and insurance mechanisms for storage.

Zusammenfassung

Das Projekt und sein Kontext. Der vorliegende Bericht fasst die Ergebnisse des Teilprojekts 3 (SP3) des Innosuisse-Flagship-Projekts DeCIRRA (Decarbonisation of Cities and Regions with Renewable Gases) zusammen. Artikel 3 des Klima- und Innovationsgesetzes (KIG) verlangt Netto-Null-Treibhausgasemissionen bis 2050, wobei Negativemissionstechnologien jenen Emissionen vorbehalten bleiben, die nicht anderweitig vermieden werden können. Auf Grundlage der Energieperspektiven 2050+ geht der Bundesrat davon aus, dass die Schweiz jährlich rund 7 Mt CO_2 an Entnahmen benötigen wird – 2 Mt im Inland und 5 Mt im Ausland – zuzüglich weiterer 5 Mt Abscheidung und Speicherung, die als Emissionsminderungen angerechnet werden. Während die übrigen DeCIRRA-Teilprojekte technischer Natur sind, ist SP3 interdisziplinär angelegt und ergänzt eine ökonomische und sozialwissenschaftliche Perspektive. Es deckt sowohl die technische CO_2-Abscheidung, -Nutzung und -Speicherung (CCUS) als auch biologische Entnahmeansätze ab: die Kohlenstoffspeicherung in Bauholz (TCCS), Bioenergie mit CO_2-Abscheidung und -Speicherung (BECCS), Biochar und Hydrochar sowie die direkte Abscheidung aus der Luft mit Speicherung (DACCS) – zusammen mit der CO_2-Transport- und Speicherinfrastruktur, von der die gasförmigen Optionen abhängen. Über die Forschung hinaus hat SP3 Expertengruppen mit Schlüsselakteuren für die Schweizer Defossilisierung aufgebaut, um Wissen auszutauschen, zu verbreiten und eine schnellere Skalierung der Ansätze zu unterstützen.

Ablauf der Arbeiten. SP3 war auf viereinhalb Jahre angelegt. In der ersten Phase sichtete das Projektteam die Literatur, beurteilte bestehende Schweizer Projekte und die für die Schweiz relevanten Kohlenstoffmanagement-Ansätze (CMA), erfasste die wichtigen Akteure und baute die Expertengruppen auf. In der zweiten Phase analysierte es laufende Kohlenstoffmanagement-Projekte und befragte Stakeholder zu ihren Rollen, ihrer Zusammenarbeit, ihrer Bedeutung und ihren Einstellungen. In der dritten Phase entstand ein Szenarienbericht, der Pfade zu Netto-Null mit einem Energiesystemmodell analysiert, einschliesslich der für die Umsetzung erforderlichen Politikmassnahmen (Guidati et al. 2024). In der Schlussphase führte es eine repräsentative Bevölkerungsbefragung zur Wahrnehmung von CO_2-Transportoptionen durch, beurteilte die weiter gefassten volkswirtschaftlichen Folgen des Netto-Null-Ziels über die Szenarien hinweg mit einem allgemeinen Gleichgewichtsmodell und analysierte Geschäftsmodelle auf Basis einer Literaturauswertung und von Interviews.

Was gegenüber dem ersten Synthesebericht neu ist. Dieser Abschlussbericht ist keine Wiederholung des Syntheseberichtes 2023. Er berücksichtigt aktualisierte Ergebnisse aus der Modellierung der CMA-Nutzung in vier Szenarien für die Defossilisierung der Schweiz bis 2050 (Octopus, Butterfly, Clam und Snail). Im Vergleich zum Szenariobericht wurde die Modellierung mit überarbeiteten Kosten und Potenzialen, Hydrochar, Abscheidung in Pyrolyseanlagen, saisonaler Auflösung im Stromsektor, Einschränkungen der Versorgungssicherheit und einer expliziten Modellierung nachhaltiger Kraftstoffe aktualisiert; zudem ist das Energiesystemmodell nun mit einem berechenbaren allgemeinen Gleichgewichtsmodell gekoppelt, um makroökonomische und Verteilungseffekte zu erfassen. Zwei empirische Komponenten sind neu: eine repräsentative Umfrage zur öffentlichen Wahrnehmung des Transports und der Speicherung von CO_2 (3.058 Befragte aus der Deutschschweiz, November 2025) sowie eine Geschäftsmodellanalyse für alle vier CMA-Ansätze. Auch die politische Landschaft hat sich rasch verändert. In der Schweiz traten im Januar 2025 das revidierte CO_2-Gesetz und das KIG in Kraft, das 1,2-Milliarden-Franken-Programm des KIG ist angelaufen, ein Rahmen-Gesetz zu CCS soll bis Ende 2026 in die Vernehmlassung gehen, und die grenzüberschreitende Speicherung wird durch die Export-Ergänzung zum Londoner Protokoll sowie bilaterale Abkommen mit Norwegen und anderen Ländern ermöglicht. Auf internationaler Ebene hat die EU ihre erste delegierte Verordnung 2026/285 über Zertifizierungsmethoden für Aktivitäten zur dauerhaften Kohlenstoffentfernung verabschiedet, und im Rahmen von Artikel 6.4 wurden Standards für die Kohlenstoffentfernung vereinbart.

Zwei CMA Optionen erweisen sich in allen Zukunftsszenarien als robust (Abbildung A). Die Verwendung von Holz im Bauwesen ist in jedem Szenario der Ansatz erster Wahl und erreicht sein modelliertes Maximalpotenzial von etwa 2 Mt CO_2 pro Jahr. Pflanzenkohle ist ebenfalls stets Teil des optimalen Mixes, mit Werten zwischen 1,66 Mt CO_2/Jahr (Butterfly) und 2,58 Mt CO_2/Jahr (Snail), während Hydrokohle nur in den Szenarien Clam und Snail mit etwa 1 Mt CO_2/Jahr zum Einsatz kommt, da für ihre Lagerung Kosten anfallen, während mit Pflanzenkohle Einnahmen erzielt werden können. Zusammen mit der CO_2-Abscheidung in Biogasanlagen bilden diese einen «No-Regret»-Cluster: heute verfügbar, auf TRL 9, unabhängig von der CO_2-Infrastruktur und eher durch regulatorische Lücken als durch technologische Unreife eingeschränkt. Inländische DAC-Maßnahmen hingegen sind in keinem der aktualisierten Szenarien Teil des optimalen Mixes: Die Zuweisung von knappem regenerativem

Strom für DAC ist nicht kosteneffizient, und die inländischen Speicherkapazitäten sind begrenzt. Die Schweiz wird eher als Technologieanbieter eine Rolle spielen als im inländischen Einsatz von DAC.

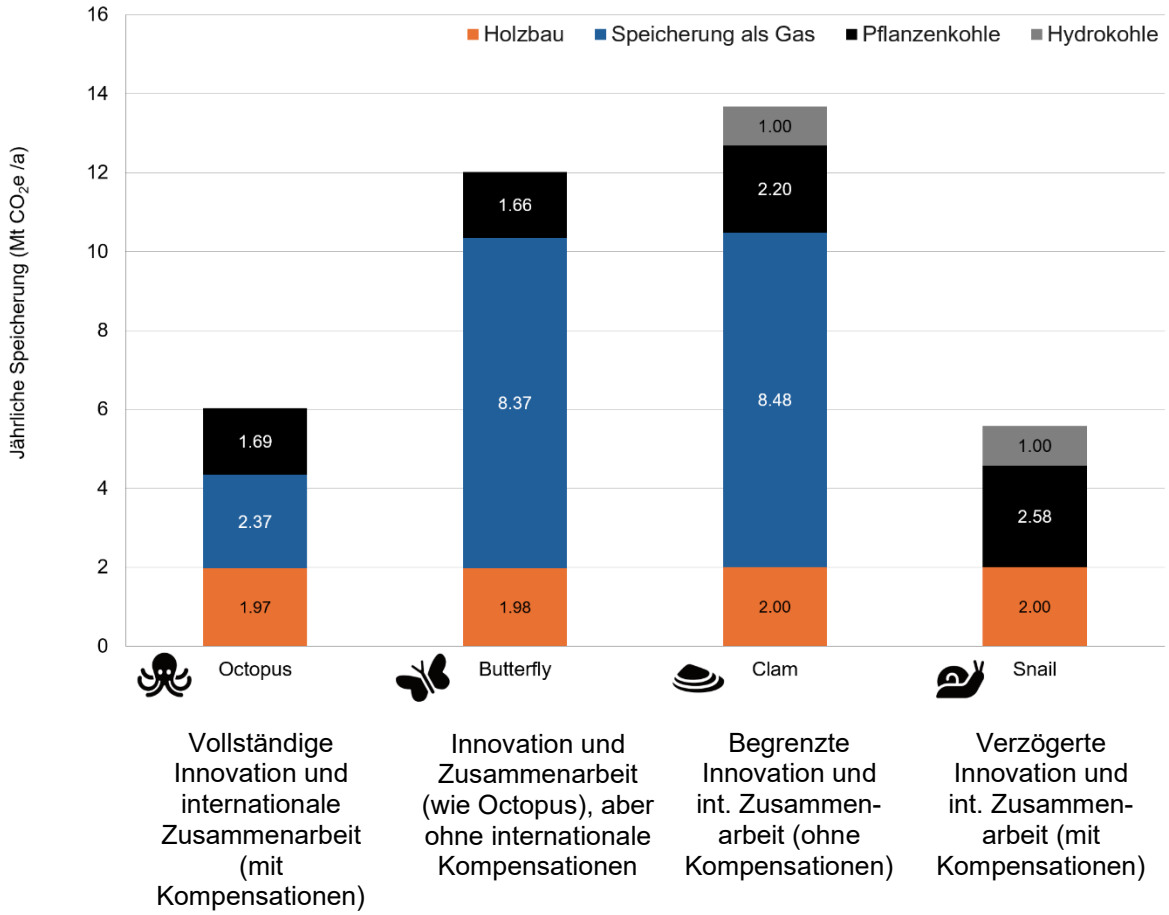


Abbildung A: Optimales CO_2-Speichermix 2050 nach Speichertypen für die vier Szenarien

Die Infrastruktur ist die entscheidende Variable. Wo internationale Kompensationen nicht verfügbar sind, wird die Abscheidung an grossen Punktquellen – Kehrichtverwertung, Zement, Chemie – dominant, wobei das CO_2 im Ausland gespeichert wird. Die Grenzvermeidungskosten bilden die angenommenen Infrastrukturkosten eng ab: Sie erreichen rund 220 CHF/tCO_{2eq} in Butterfly, wo CO_2-Transport und -Speicherung günstig sind, gegenüber 1'500 CHF/tCO_{2eq} in Clam, wo diese Kosten als prohibitiv angenommen worden sind, um zu demonstrieren, was die Auswirkungen wären, wenn die Zusammenarbeit mit der EU scheitert. Bei diesen hohen Kosten im Clam Szenario dürfte das Netto-Null-Ziel kaum die nötige politische und gesellschaftliche Unterstützung finden. Daraus folgt, dass die CO_2-Transport- und Speicherinfrastruktur möglichst schnell geklärt werden sein sollte.

Die volkswirtschaftlichen Kosten übersteigen die Energiesystemkosten. Die Szenarien „Butterfly" und „Octopus" basieren auf denselben technologischen Annahmen; sie unterscheiden sich lediglich darin, ob die letzten 6 Mt im Inland eingespart werden („Butterfly") oder zu denselben Grenzkosten im Ausland eingekauft werden („Octopus"). Die allgemeine Gleichgewichtsanalyse berücksichtigt, dass der Kauf von Emissionsgutschriften im Ausland die Terms of Trade der Schweiz verschlechtert, wodurch die Wohlfahrtsverluste im Szenario „Octopus" um etwa 25 % höher ausfallen als im Szenario „Butterfly". Damit Emissionsgutschriften wohlfahrtsoptimal sind, müssten sie etwa 36 % günstiger sein als eine inländische Reduktion, was schwierig erscheint, da Emissionsgutschriften von hoher Qualität und mit hoher Umweltintegrität nicht günstig sein werden. Eine Verzögerung ist noch schädlicher: Die Wohlfahrtskosten des „Snail"-Szenarios sind mehr als 2,5-mal so hoch wie die des „Butterfly"-Szenarios. Eine aktive Strategie, die Innovationen, internationale Zusammenarbeit im Bereich CO_2-Transport- und Speicherinfrastruktur und inländische Reduktion kombiniert, ist das günstigste der vier Szenarien.

Nicht die Technologie, sondern die Regulierung schafft den Markt. Über alle CMA hinweg besteht ohne regulatorischen Eingriff kein kommerzieller Business Case, da CO_2-Entnahme ein öffentliches Gut ist, dessen Wert durch politische Maßnahmen festgelegt werden muss. Die Analyse identifiziert derzeit ein dreifaches Marktversagen: minimale Integration in Compliance-Märkte, fehlende Transport- und

Speicherinfrastruktur sowie fehlende Zertifizierungsstandards für einige Ansätze. Die Rentabilität hängt derzeit von den zusätzlichen Einnahmen ab – insbesondere den Verkauf von Pflanzenkohle – und von den Verkäufen am freiwilligen Markt. Eine Befragung von rund 140 Stakeholdern aus vier Akteursgruppen (grosse Punktquellen-Emittenten, Anbieter von Entnahmetechnologien und -dienstleistungen, Regulierungsbehörden sowie unterstützende Dienstleister) ergab breiten Konsens darüber, dass ein CO_2-Preis das zentrale Instrument ist, gefolgt von verbindlichen Zielvorgaben, die insbesondere von den Regulierungsbehörden bevorzugt werden. BAFU und BFE wurden als wichtigste Akteure gesehen, gefolgt von den Kehrichtverwertungsanlagen, den Eidgenössischen Technischen Hochschulen und der Politik; die Zementindustrie ist wichtig, aber weniger gut eingebunden. Für die Marktbildung ergeben sich daraus vier Massnahmen: die öffentliche Beschaffung zertifizierter Schweizer CO_2-Entfernungsdienstleistungen als unmittelbarer Nachfragestimulus, die Wiedereinführung des BFE-Demonstrationsprogramms mit zweckgebundenen Finanzierungsströmen, die Neugestaltung der KIG-Förderung, um Projekten in der Frühphase leicht zugängliche Pilotmöglichkeiten zu bieten, sowie „Carbon Contracts for Difference“ als Instrument zur Risikoteilung und Skalierung, das die Lücke zwischen den aktuellen CO_2-Preisen und den für die kostspieligeren CMA erforderlichen Preisen schliessen kann.

Anrechnung und Zertifizierung der Holzspeicherung im Bauwesen bleiben ungelöst. Ökobilanzierung, Anrechnung im nationalen Treibhausgasinventar und projektbezogene Anrechnung auf Kohlenstoffmärkten werden häufig vermischt und müssen klar auseinandergehalten werden. Der zentrale Streitpunkt besteht darin, dass fossile CO_2 Emissionen die Atmosphäre über Jahrtausende erwärmt, während die meisten verfügbaren Ansätze auf Biomassebasis den Kohlenstoff über weit kürzere Zeiträume speichern. Drei Ansätze wurden diskutiert ohne, dass ein Konsens erzielt werden konnte. Für TCCS vergleicht der Bericht den HWP-Pool-Ansatz, der dem Programm «Senke Schweizer Holz» zugrunde liegt, mit Alternativen auf Projekt- und Wertschöpfungskettenebene. Welches Politikmix bzw. Politikabfolge sich für TCCS am besten eigenen würde, sollte weiter analysiert werden. Klar ist, dass die Nachfrage nach TCCS Zertifikaten nicht aus dem Transportsektor kommen sollte, da dieser nicht zu den schwer vermeidbaren Emissionen zählt und die derzeitigen Schweizer Permanenzanforderungen von 30 Jahren international nicht kompatibel sind. Daher sollte die Möglichkeit TCCS zur Kompensation von kurz-lebigen Treibhausgasen wie Methan zu nutzen geprüft werden sollten.

Die Akzeptanz in der Bevölkerung ist höher als gemeinhin angenommen, aber uneinheitlich. Über alle sechs in der repräsentativen Befragung getesteten CO_2-Transportoptionen hinweg standen rund 88% der Befragten neutral oder zustimmend dazu, und nur etwa 12% lehnten sie ab (Abbildung B). Umgenutzte Pipelines werden deutlich besser akzeptiert als Neubauten, und die Information der Befragten darüber, dass in der Schweiz bereits heute CO_2 für industrielle Zwecke transportiert wird, erhöhte die Zustimmung bei jeder einzelnen Transportoption. Das deutet darauf hin, dass grössere Kommunikationsanstrengungen nötig sind – insbesondere, indem die Öffentlichkeit aktiv über die bereits stattfindenden CO_2-Transporte informiert wird.

Die Ablehnung hängt eher mit dem Alter, einer geringeren Klimasorge und geringerem Vertrauen zusammen als mit dem Einkommen oder der Region. Die Speicherung ist der Schwachpunkt: 60 % haben Bedenken gegenüber der geologischen CO_2-Injektion, gegenüber etwa 26 % bei der unterirdischen Lagerung von fester Pflanzenkohle, obwohl 73 % die geologische Speicherung im Inland grundsätzlich befürworten, sofern sie sicher durchgeführt werden kann – eine Herausforderung, die eher mit Vertrauensbildung als mit grundsätzlicher Ablehnung zu tun hat.

Die Ausgestaltung der Verteilungswirkungen ist entscheidend. Ordnungsrechtliche Vorgaben (Command-and-Control) wirken in jedem Szenario progressiv, während die Finanzierung von CCS an Kehrichtverwertungsanlagen über die Abfallgebühren der Haushalte regressiv wirkt und Anreize zu illegaler Müllentsorgung schaffen kann. Als Alternative könnte die Ausweitung des vorgezogenen Recyclingbeitrags auf Produzenten und Importeure von Kunststoffverpackungen geprüft werden: Damit fielen die CO_2-Kosten beim Markteintritt an – dort, wo die Materialentscheide getroffen werden und das Substitutionspotenzial am grössten ist.

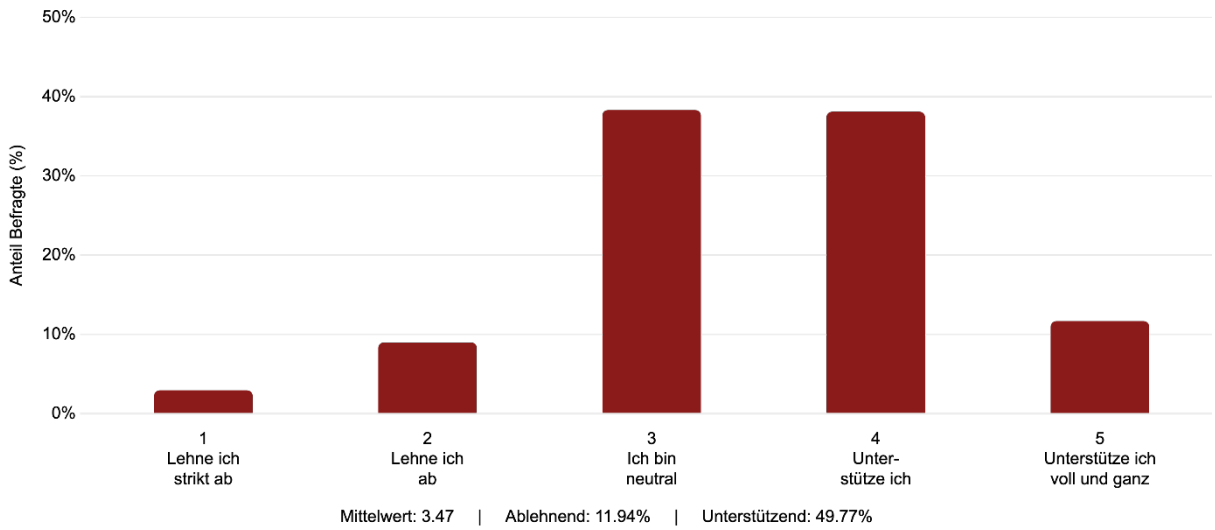


Abbildung B: Häufigkeit über alle sechs Transportoptionen hinweg: "Wieweit unterstützen Sie diesen möglichen Transportweg zu einer permanenten CO_2-Speicherstätte? "

Prioritäten. Frühzeitig Zugang zu europäischen CO_2-Speichern sichern und gleichzeitig inländische Kapazitäten aufbauen; stabile, international kompatible Investitionsrahmen schaffen, die den grössten verfügbaren Hebel zur Kostensenkung darstellen; die regulatorischen Hürden für Pflanzenkohle und Hydrochar beseitigen; inländische Minderungen und Entnahmen gegenüber teuren internationalen Kompensationszertifikaten bevorzugen. Detaillierte Politikempfehlungen finden sich im abschliessenden Abschnitt 6. Offener Forschungsbedarf besteht bei der regional aufgelösten Modellierung von Infrastrukturpfaden, bei langfristigen Schweizer Daten zur Permanenz von Biochar und zu dessen Bodenwirkungen, bei der Quantifizierung und den Integrationsmöglichkeiten von Zusatznutzen und externen Kosten, bei Anrechnungs- und Anreizsystemen für TCCS, bei einer detaillierten Analyse eines Recyclingbeitrags von Produzenten und Importeuren von Kunststoffverpackungen zugunsten der Kehrichtverwertungsanlagen sowie bei der Ausgestaltung von Haftungs- und Versicherungsmechanismen für die Speicherung.

Résumé exécutif

Le projet et son contexte. Le présent rapport synthétise les résultats du sous-projet 3 (SP3) du projet Flagship Innosuisse DeCIRRA (Decarbonisation of Cities and Regions with Renewable Gases). L'article 3 de la loi fédérale sur le climat et l'innovation (LCI / KIG) impose la neutralité des émissions de gaz à effet de serre d'ici à 2050, les technologies à émissions négatives étant réservées aux émissions qui ne peuvent être évitées autrement. Sur la base des Perspectives énergétiques 2050+, le Conseil fédéral estime que la Suisse aura besoin d'environ 7 Mt de CO_2 d'absorptions par an – 2 Mt sur le territoire national et 5 Mt à l'étranger – auxquelles s'ajoutent 5 Mt de captage et de stockage comptabilisés comme réductions d'émissions. Alors que les autres sous-projets de DeCIRRA sont de nature technique, le SP3 est interdisciplinaire et apporte une perspective économique et de sciences sociales. Il couvre à la fois le captage, l'utilisation et le stockage techniques du carbone (CCUS) et les approches biologiques d'absorption : le stockage du carbone dans le bois de construction (TCCS), la bioénergie avec captage et stockage du carbone (BECCS), le biochar et l'hydrochar, ainsi que le stockage direct du carbone atmosphérique (DACCS), de même que l'infrastructure de transport et de stockage du CO2 dont dépendent les options gazeuses. Au-delà de la recherche, le SP3 a mis en place des groupes d'experts réunissant les acteurs clés de la défossilisation en Suisse, afin de diffuser les connaissances et de soutenir une mise à l'échelle plus rapide.

Déroulement des travaux. Le SP3 s'est déroulé sur quatre ans et demi. Dans une première phase, l'équipe de projet a analysé la littérature, évalué les projets suisses existants ainsi que les approches de gestion du carbone (CMA) pertinentes pour la Suisse, cartographié les acteurs importants et constitué les groupes d'experts. Dans une deuxième phase, elle a analysé les projets de gestion du carbone en cours et interrogé les parties prenantes sur leurs rôles, leur coopération, leur importance et leurs attitudes. Au cours de la troisième phase, elle a produit un rapport de scénarios analysant les trajectoires vers le zéro net à l'aide d'un modèle du système énergétique, y compris les politiques nécessaires à leur mise en œuvre (Guidati et al. 2024). Dans la phase finale, elle a mené une enquête représentative auprès de la population sur la perception des options de transport du CO_2, évalué les conséquences économiques plus larges de l'objectif zéro net dans les différents scénarios au moyen d'un modèle d'équilibre général calculable, et analysé les modèles d'affaires sur la base d'une revue de la littérature et d'entretiens.

Quelles sont les nouveautés par rapport au premier rapport de synthèse ? Ce rapport final n'est pas une reprise de la synthèse de 2023. Il intègre des résultats actualisés issus de la modélisation du recours aux CMA selon quatre scénarios de décarbonation de la Suisse à l'horizon 2050 (Octopus, Butterfly, Clam et Snail). Par rapport au rapport de scénarios, la modélisation a été actualisée avec des coûts et des potentiels révisés, l'hydrochar, le captage dans les installations de pyrolyse, une résolution saisonnière dans le secteur de l'électricité, des contraintes de sécurité d'approvisionnement et une modélisation explicite des carburants durables ; le modèle du système énergétique est en outre désormais couplé à un modèle d'équilibre général calculable, afin de saisir les effets macroéconomiques et distributifs. Deux volets empiriques sont nouvelles : une enquête représentative sur la perception par la population du transport et du stockage du CO_2 (3 058 personnes interrogées en Suisse alémanique, novembre 2025) et une analyse des modèles d'affaires portant sur les quatre approches CMA. Le cadre politique a lui aussi évolué rapidement. En Suisse, la loi révisée sur le CO_2 et la LCI sont entrées en vigueur en janvier 2025, le programme de 1,2 milliard de francs prévu par la LCI est opérationnel, une loi-cadre sur le CSC doit être mise en consultation d'ici à la fin de 2026, et le stockage transfrontalier est rendu possible par l'amendement du Protocole de Londres relatif à l'exportation ainsi que par des accords bilatéraux avec la Norvège et d'autres pays. Sur le plan international, l'UE a adopté son premier règlement délégué 2026/285 relatif aux méthodologies de certification des activités d'absorption permanente du carbone, et des normes d'absorption ont été arrêtées au titre de l'article 6.4.

Deux options sont robustes dans tous les les scénarios (Figure A). L'utilisation du bois dans la construction est l'approche prioritaire dans chaque scénario, atteignant son potentiel maximal modélisé d'environ 2 Mt de CO_2 par an. Le biochar fait également toujours partie du mix optimal, avec des valeurs comprises entre 1,66 Mt de CO_2/an (scénario « Butterfly ») et 2,58 Mt de CO_2/an (scénario « Snail »), tandis que l'hydrochar n'apparaît que dans les scénarios « Clam » et « Snail » à environ 1 Mt de CO_2/an, car son stockage doit être financé alors que le biochar peut générer des revenus. Associées au captage du CO_2 dans les installations de biogaz, ces technologies forment un ensemble « sans regret » : disponibles dès aujourd'hui, au niveau TRL 9, indépendantes des infrastructures de CO_2, et limitées par des lacunes réglementaires plutôt que par une immaturité technologique. En revanche, le DAC national ne fait partie du mix optimal dans aucun scénario actualisé : affecter de l'électricité à faible émission de carbone, une ressource rare, au DAC n'est pas rentable, et les capacités de stockage nationales sont

limitées. Le rôle de la Suisse réside davantage dans la chaîne de valeur technologique que dans le déploiement national.

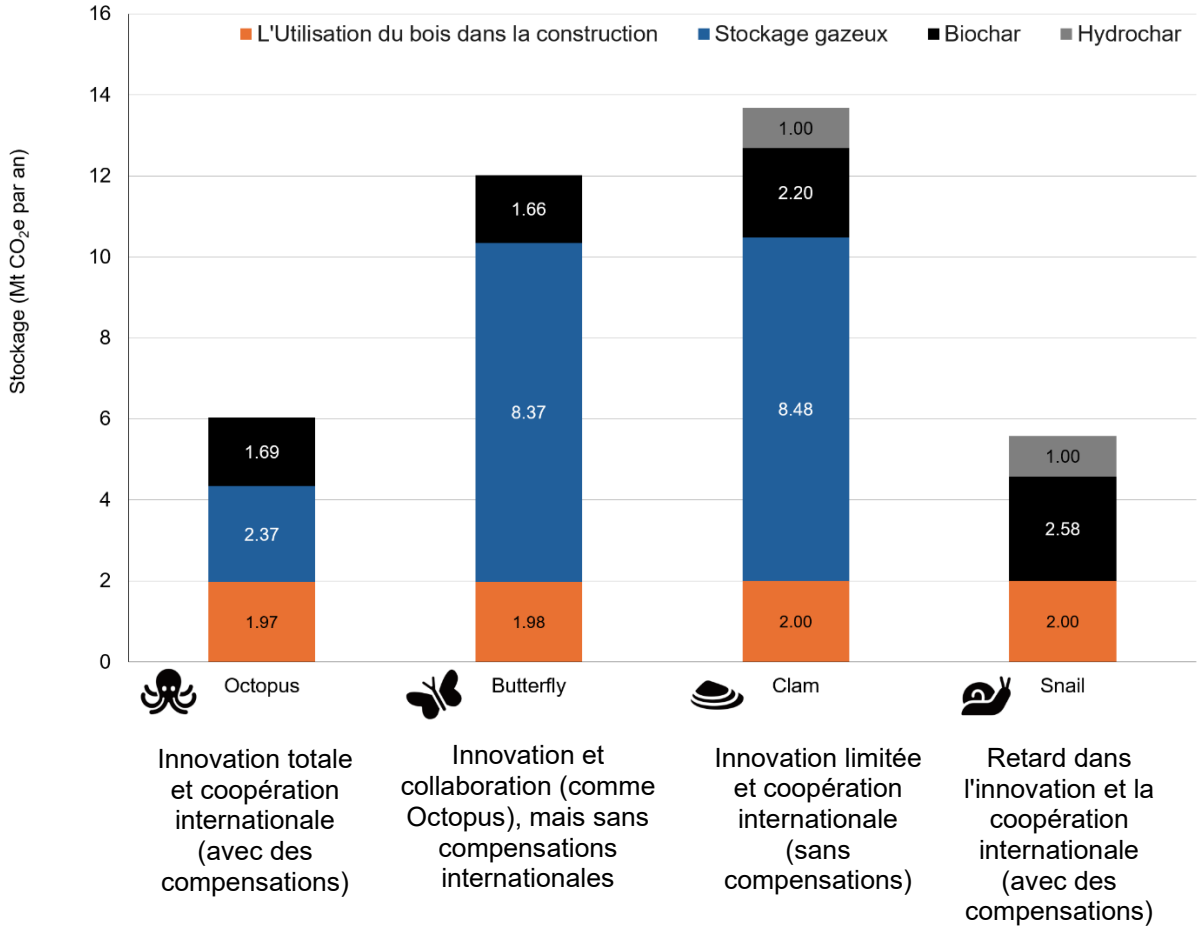


Figure A : Composition optimale des types de stockage du CO_2 en 2050 selon les quatre scénarios

Les infrastructures constituent la variable déterminante. Lorsque les compensations internationales ne sont pas disponibles, le captage au niveau des grandes sources ponctuelles – incinération des déchets, cimenterie, industrie chimique – devient prédominant, le CO_2 étant stocké à l'étranger. Les coûts marginaux de réduction reflètent étroitement les coûts d'infrastructure supposés : ils s'élèvent à environ 220 CHF/tCO_2e dans le scénario « Butterfly », où le transport et le stockage du CO_2 sont peu coûteux, contre 1 500 CHF/tCO_2e dans le scénario « Clam », où les coûts ont été supposés prohibitifs afin d'illustrer de l'échec de la coopération avec l'UE. À ce niveau de coûts, la réalisation de l'objectif de zéro émission nette a peu de chances de bénéficier d'un soutien politique et public suffisant. Comme ni les opérateurs de captage ni les fournisseurs d'infrastructures ne sont disposés à investir en premier, le gouvernement fédéral joue un rôle de coordinateur indispensable.

Les coûts économiques dépassent ceux du système énergétique. Les scénarios « Butterfly » et « Octopus » partagent les mêmes hypothèses technologiques ; ils ne diffèrent que sur la question de savoir si les 6 Mt restantes sont réduites sur le territoire national (« Butterfly ») ou achetées à l'étranger au même coût marginal (« Octopus »). L'équilibre général tient compte du fait que l'achat de crédits de compensation à l'étranger détériore les termes de l'échange de la Suisse, ce qui entraîne des pertes de bien-être d'environ 25 % plus élevées dans le scénario « Octopus » que dans le scénario « Butterfly ». Pour que les compensations soient optimales en termes de bien-être, elles devraient être environ 36 % moins chères que la réduction nationale, ce qui semble difficile à réaliser car les compensations de haute qualité et garantissant l'intégrité environnementale seront plus coûteuses. Le report des mesures est encore plus préjudiciable : le coût en termes de bien-être du scénario « Snail » est plus de 2,5 fois supérieur à celui du scénario « Butterfly ». Une stratégie active combinant innovation, coopération internationale et réduction sur le territoire national est la plus favorable des quatre scénarios.

C'est la réglementation, et non la technologie, qui crée le marché. Quelle que soit l'approche de gestion du carbone, aucune viabilité commerciale n'est possible sans intervention réglementaire, car la séquestration est un bien public dont la valeur doit être fixée par les pouvoirs publics. L'analyse met en

évidence une triple défaillance du marché à l'heure actuelle : une intégration minimale dans les marchés de conformité, un manque d'infrastructures de transport et de stockage, et l'absence de normes de certification pour certaines approches. L'adoption de ces solutions repose aujourd'hui sur des avantages connexes – notamment les ventes de biochar – et sur le marché volontaire. Une enquête menée auprès d'environ 140 parties prenantes réparties en quatre groupes d'acteurs (grands émetteurs ponctuels, fournisseurs de technologies et de services de séquestration, régulateurs et prestataires de services d'appui) a révélé un large consensus sur le fait qu'un prix du CO_2 constitue l'instrument clé, suivi par des objectifs contraignants, privilégiés en particulier par les régulateurs. L'OFEV et l'OFEN ont été considérés comme les acteurs les plus importants, suivis par les usines d'incinération des déchets, les Écoles polytechniques fédérales et les responsables politiques ; l'industrie du ciment est importante mais moins bien intégrée. Quatre mesures sont proposées pour favoriser la formation du marché : les marchés publics de services de séquestration certifiés suisses comme stimulant immédiat de la demande, la réinstauration du programme de démonstration de l'OFEN avec des sources de financement dédiées, la refonte du soutien de la KIG afin d'offrir aux projets en phase de démarrage des opportunités de projets pilotes à bas seuil, et les contrats de différence carbone (Carbon Contracts for Difference) comme instrument de mise à l'échelle avec partage des risques, capable de combler l'écart entre les prix actuels du carbone et les prix nécessaires pour les mesures de séquestration plus coûteuses.

La comptabilisation et la certification du stockage du carbone dans le bois de construction restent en suspens. L'analyse du cycle de vie, la comptabilisation dans l'inventaire national et la comptabilisation au niveau des projets sur les marchés du carbone sont fréquemment confondues et doivent être clairement distinguées. La question centrale, controversée, tient au fait que le CO2 fossile réchauffe l'atmosphère durant des millénaires, alors que la plupart des approches disponibles fondées sur la biomasse stockent le carbone pour des durées bien plus courtes. Quatre réponses sont débattues sans qu'un consensus se dégage, et le rapport méthodologique du GIEC sur le CDR, le CSC et le CCU, attendu d'ici à la fin de 2027, sera déterminant. L'exigence suisse de permanence de 30 ans est en décalage avec la pratique internationale. Pour le TCCS, le rapport compare l'approche par réservoir de produits ligneux récoltés (HWP), qui sous-tend le dispositif « Senke Schweizer Holz », avec des solutions au niveau des projets et de la chaîne de valeur. Une comparaison structurée des options, tenant compte des évolutions internationales, est nécessaire à temps pour la révision de la politique climatique suisse en 2030. Il est clair que la demande ne devrait pas provenir du secteur des transports, car celui-ci ne fait pas partie des secteurs aux émissions difficilement évitables. De plus, l'exigence de permanence de 30 ans actuellement en vigueur en Suisse n'est pas compatible avec les standards internationaux. Il conviendrait donc d'examiner la possibilité d'utiliser le TCCS pour compenser des gaz à effet de serre à courte durée de vie, comme le méthane.

L'acceptation par la population est plus élevée qu'on ne le suppose généralement, mais elle est inégale. Pour l'ensemble des six options de transport testées dans l'enquête représentative, environ 88 % des personnes interrogées se sont déclarées neutres ou favorables, et seules quelque 12 % s'y sont opposées (Figure B). Les conduites reconverties sont nettement mieux acceptées que les constructions nouvelles, et le fait d'informer les répondants que du CO_2 est déjà transporté en Suisse à des fins industrielles a accru le soutien pour chacune des options de transport. Cela indique qu'un effort de communication accru est nécessaire, en particulier en informant activement la population sur les transports de CO_2 qui ont déjà lieu.

L'opposition est corrélée à l'âge, à une moindre préoccupation climatique et à une confiance plus faible, plutôt qu'au revenu ou à la région. Le stockage constitue le point faible : 60 % des personnes interrogées se disent mal à l'aise avec l'injection géologique de CO_2, contre environ 26 % pour le biochar solide stocké dans le sol, même si 73 % soutiennent sur le principe un stockage géologique en Suisse s'il peut être réalisé en toute sécurité – un enjeu de construction de la confiance plutôt qu'une opposition de fond.

La conception des effets distributifs est déterminante. Une réglementation de type « commandement et contrôle » a un effet progressif dans tous les scénarios, tandis que le financement du CSC dans les usines d'incinération des déchets par le biais des redevances sur les déchets ménagers est régressif et risque d'encourager les déversements illégaux. L'extension de la contribution préalable au recyclage aux producteurs et importateurs d'emballages en plastique pourrait être envisagée comme une alternative, en plaçant le coût du carbone au moment de l'entrée sur le marché, là où les choix de matériaux sont effectués et où le potentiel de substitution est le plus élevé.

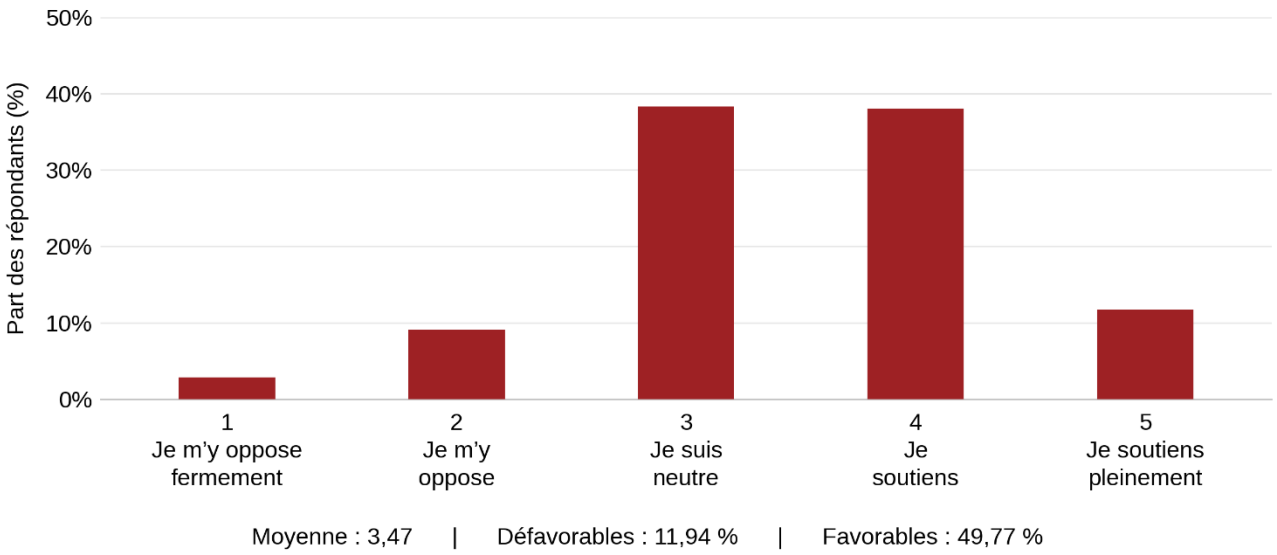


Figure B : Répartition des réponses pour les six options de transport : « Dans quelle mesure soutenez-vous cet itinéraire de transport potentiel vers un site de stockage permanent de CO_2 ? »

Priorités. Sécuriser rapidement l'accès aux capacités européennes de stockage du CO_2 tout en développant les capacités nationales ; établir des cadres d'investissement stables et compatibles sur le plan international, qui constituent le principal levier de réduction des coûts disponible ; lever les obstacles réglementaires au biochar et à l'hydrochar ; privilégier les réductions et les absorptions nationales par rapport aux compensations. Les recommandations politiques détaillées figurent à la section 6 finale. Les besoins de recherche restants comprennent une modélisation régionalisée des trajectoires d'infrastructure, des données suisses de long terme sur la permanence du biochar et ses effets sur les sols, la quantification et les options d'intégration des co-bénéfices et des coûts externes, les schémas de comptabilisation et d'incitation pour le TCCS, une analyse détaillée d'une contribution de recyclage due par les producteurs et importateurs d'emballages plastiques au bénéfice des usines d'incinération des ordures ménagères, ainsi que la conception de mécanismes de responsabilité et d'assurance pour le stockage.

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Acronyms and definitions

The following definitions were mostly obtained from the latest IPCC Glossary (Intergovernmental Panel on Climate Change (IPCC) 2023). Other sources are mentioned in the respective paragraphs.

Accounting (Cowie et al. 2006; Intergovernmental Panel on Climate Change (IPCC) 2006; UNFCCC 2003 para. 16): "The rules for comparing emissions and removals, as reported, with commitments assumed by Annex I Parties under the Kyoto Protocol." Thus, accounting means calculating 'debits' and 'credits' with reference to the agreed target. Accounting under the Kyoto Protocol was restricted to a specific set of anthropogenic activities. It is expected that accounting will take as its basis the estimates produced for inventory reporting, to ensure consistency and minimize additional effort, but it can include political elements (e.g., caps, discounting) agreed in negotiations between Parties.

Adverse side-effect: A negative effect that a policy or measure aimed at one objective has on another objective, thereby potentially reducing the net benefit to society or the environment.

Anthropogenic removals: The withdrawal of greenhouse gases (GHGs) from the atmosphere as a result of deliberate human activities. These include enhancing biological sinks of CO_2 and using chemical engineering to achieve long-term removal and storage. Carbon capture and storage (CCS), which alone does not remove CO_2 from the atmosphere, can help reduce atmospheric CO_2 from industrial and energy-related sources if it is combined with bioenergy production (BECCS), or if CO_2 is captured from the air directly and stored (DACCS).

Biochar: Relatively stable, carbon-rich material produced by heating biomass in an oxygen-limited environment (pyrolysis). Due to this process, decomposition of the biomass feedstock back into CO_2 is avoided. This CDR method is also called Biochar Carbon Removal (BCR). Biochar can be used as a soil amendment where it typically improves soil functions. BCR can also be affected via durable storage in building materials. [1]

BiCRS: BiCRS (Biomass Carbon Removal and Storage) removes CO_2 from the atmosphere by converting biomass into a stable carbon form and storing it permanently.

BioCCS: Biogenic emissions capture with carbon storage activity means an activity resulting in a process of capturing biogenic CO_2 followed by transport and permanent storage of that biogenic CO_2 by injection at a geological storage site (EU Commission 2026/285). In contrast to BECCS BioCCS is a broader concept and uses biomass, regardless of whether energy is the primary output. This includes, for example, CO_2 released during bioethanol fermentation or biogas upgrading.

Bioenergy: Energy derived from any form of biomass or its metabolic by-products.

Carbon dioxide removal (CDR): Anthropogenic activities removing carbon dioxide (CO_2) from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical CO_2 sinks and direct air carbon dioxide capture and storage (DACCS), Bioenergy and carbon capture and storage (BECCS) and Biochar Carbon Removal (BCR), but excludes natural CO_2 uptake not directly caused by human activities.

Carbon Pool: A reservoir in the *Earth System* where carbon resides in various chemical forms for a period of time (Glossary IPCC 2022a).

Carbon storage in products means any practice or process that captures and stores atmospheric or biogenic carbon for at least 35 years in long-lasting products, allows on-site monitoring of the carbon stored and is certified throughout the monitoring period (CRCF Regulation).

Climate Smart Forestry (CSF): Climate Smart Forestry (CSF) is a new branch of sustainable forest management that aims to manage forests in a way that is optimised for climate change. Specific CSF strategies are seen as a way to develop appropriate management measures and improve the provision of ecosystem services.

[1] See also https://biochar-international.org/about-biochar/faqs/.

Co-benefits: A positive effect that a policy or measure aimed at one objective has on another objective, thereby increasing the total benefit to society or the environment. Co-benefits are also referred to as ancillary benefits.

Direct air carbon dioxide capture and storage (DACCS): Chemical process by which carbon dioxide (CO_2) is captured directly from the ambient air, with subsequent storage. Also known as direct air capture and storage (DACS).

Durability: A metric for permanence that comprises two components: the timeframe credited carbon dioxide equivalent *is held out of the atmosphere*; and the likelihood the carbon dioxide equivalent will remain stored for this timeframe (Gupton et al. 2026).

Leakage: The effects of policies that result in a displacement of the environmental impact, thereby counteracting the intended effects of the initial policies.

Net-zero GHG emissions: Condition in which metric weighted anthropogenic GHG emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period. The quantification of net-zero GHG emissions depends on the GHG emission metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric.

Net-zero emissions (KIG Art. 2): largest possible reduction of GHG emissions and compensation of the impact of remaining emissions through the use of negative emission technologies.

Permanence: Period during which CO_2 is temporarily stored and removed from the atmosphere and the associated climate effects in the form of a delayed atmospheric temperature rise. In most cases, CO_2 that is stored for 100 years or more is considered "permanently removed" (de Kleijne et al. 2022; Terlouw, Bauer, et al. 2021).

Removal (or Carbon Dioxide Removal, CDR) anthropogenic *activities* removing carbon dioxide (CO_2) from the atmosphere and *durably storing* it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical CO_2 ***sinks*** and direct air carbon dioxide capture and storage (DACCS), but *excludes natural CO_2 uptake* not directly caused by human activities (Glossary IPCC 2022a). Unlike a sink, a removal implies intentionality, quantifiability, and accountability, and is therefore the term used in climate policy, carbon markets, and net-zero accounting frameworks. A natural sink can generate removals if it is actively managed and carbon uptake is monitored and credited, but the two are not interchangeable. A sink that is not measured, verified, and attributed does not qualify as a removal under most accounting frameworks (CRCF Regulation).

Reporting (Cowie et al. 2006; Intergovernmental Panel on Climate Change (IPCC) 2006; UNFCCC 2003 para. 16)**:** The action of providing the results of the estimation of emissions and removals to the UNFCCC in a standardised manner. This usually refers to the submission of national GHG inventories to the UNFCCC. Reporting is intended to isolate the anthropogenic component of estimated emissions and removals.

Reservoir A component or components of the *climate system* where a GHG or a precursor of a GHG is stored (UNFCCC Article 1.7, see Glossary IPCC 2022b). It refers to the *physical medium or location* in which carbon is held, whether temporarily or permanently; for example, biomass, timber in buildings, soils, or geological formations. A reservoir can function as a ***sink*** when it accumulates carbon on net, but may become a source of disturbance, decay, or harvest causes it to release more CO_2 than it absorbs (IPCC 2022b).

Reversal: the voluntary or involuntary release back into the atmosphere of carbon captured and stored by an activity. (CRCF Regulation)

Sequestration The *process* of storing carbon in a carbon ***pool*** (Glossary IPCC 2022a) refers to the *process by which carbon is captured and stored in a* ***reservoir***, whether through biological, chemical, or physical mechanisms. It describes the *act of transfer* from the atmosphere into a storage medium; for example, photosynthesis transferring CO_2 into biomass, or the injection of captured CO_2 into geological formations. Sequestration is thus the mechanism that enables both sinks and removals to function: a sink sequesters carbon continuously, while a CDR activity is specifically designed to maximise and account for sequestration.

Sink Any *process*, activity or mechanism which removes a GHG, an aerosol or a precursor of a GHG from the atmosphere. (Glossary IPCC 2022a) For example: growing forests, soils, or geological ***storage*** via CCS. The defining characteristic is the net flow: uptake must exceed release. Importantly, a sink can exist passively without human intervention, such as through natural forest growth.

Social costs: The full costs of an action in terms of social welfare losses, including external costs associated with the impacts of this action on the environment, the economy (GDP, employment) and on the society as a whole.

Storage refers to the *containment of carbon in a **reservoir** over time*, following ***sequestration***. It describes the *state of retention* rather than the act of capture; that is, how long and how securely carbon remains out of the atmosphere once it has been sequestered. Storage can be biological (e.g. carbon held in living biomass, soils, or harvested wood products), chemical (e.g. carbon mineralised into stable compounds), or geological (e.g. CO_2 injected into deep saline aquifers or depleted hydrocarbon reservoirs or solid carbon in underground cavities).

Abbreviations

A6.4ERs	Article 6.4 Emission Reductions
ADWO	Ordinance on the Prevention and Disposal of Waste
AER	Federal Office for Spatial Development
AFOLU	Agriculture, Forestry, and Land-use
AGIR	Arbeitsgruppe Interventionswerte und Risikobeurteilung (Soil Protection Working Group on Intervention Values and Risk Assessment, Cercle Sol)
BAU	Business as usual
BCR	Biochar Carbon Removal
BECCS	Bioenergy with Carbon Capture and Storage; Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility. Note that, depending on the total emissions of the BECCS supply chain, carbon dioxide (CO_2) can be removed from the atmosphere.
BFH	Bern University of Applied Sciences
BiCRS	Biomass with Carbon Removal and Storage
BioCCS	Biogenic emissions Capture with Carbon Storage
BSCR	Bio-based Solid Carbon Removal
BSI	British Standards Institution
CAPEX	Capital expenditures
CBAM	Carbon Border Adjustment Mechanism
CC	Carbon capture
CCfD	Carbon contracts for difference
CCP	Core Carbon Principles
CCS, CCU, CCUS	Carbon Dioxide Capture and Storage / Utilisation; A process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere. Sometimes referred to as Carbon Capture and Storage. Utilisation: A process in which carbon dioxide (CO_2) is captured and the carbon then used in a product. The climate effect of CCU depends on the product lifetime, the product it displaces, and the CO_2 source (fossil, biomass or atmosphere). CCU is sometimes referred to as Carbon Dioxide Capture and Use, or Carbon Capture and Utilisation.
CCTS	Carbon capture, transport and storage
CCT(U)S	Carbon capture, transport, (utilisation) and storage
CDM	Clean Development Mechanism
CDR	Carbon Dioxide Removal
CGE	Computable general equilibrium
CH4	Methane
CHP	Combined heat and power plant
CITru	CO_2 Pilot Injection in Trüllikon (pilot project)
CMA	Carbon Management Approaches
CMT	Carbon Management Technologies
CO_2	Carbon dioxide
CRCF	EU Carbon Removals and Carbon Farming Regulation
CRL	Commercial Readiness Levels
CSF	Climate Smart Forestry
CSI	Carbon Standars International
CSP	CO_2 Pipeline Schweiz AG
DAC	Direct air capture
DA(C)C	Direct Air (Carbon) Capture
DACC	Direct air carbon capture
DACCS	Direct Air Carbon Capture and Storage
DACH	Germany, Austria and Switzerland (Deutschland, Österreich, Schweiz)

DACS	Direct air capture and storage
DeCIRRA	decarbonisation of Cities and Regions with Renewable Gases
DemoUpCarma	Demonstration and Upscaling of Carbon Dioxide Management Solutions
DETEC	Federal Department of the Environment, Transport, Energy and Communications
DM	Dry matter
EBC	European Biochar Certification
EFK	Eidgenössische Finanzkontrolle (Swiss Federal Audit Office)
Empa	Swiss Federal Laboratories for Materials Science and Technology
e-NG	Renewable synthetic methane
EPA	Environmental Protection Act
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declaration
ETHZ / ETH Zurich	Federal Institute of Technology Zurich
ETS	Emissions Trading Scheme
EU ETS	European Union Emissions Trading Scheme
EV	Equivalent variation
FDFA	Federal Department of Foreign Affairs
FEED	Front-end engineering design
FiBl	Research Institute of Organic Agriculture
FLh	Full load hours
FOAG	Federal Office for Agriculture
FOAK	First-of-a-kind (plant)
FOEN	Federal Office for the Environment
FOT	Federal Office of Transport
FPI	Federal Pipelines Inspectorate
FRU	Fachkreis Raumplanung im Untergrund
FSC	Forest Stewardship Council
GDP	Gross domestic product
GE	General equilibrium
GEMENE	Computable general equilibrium model of the Swiss economy
GGR	Greenhouse gas removals
GHG	Greenhouse gas
GRegio	GRegio Energie AG
HEPIA Geneva	Geneva School of Landscape, Engineering and Architecture - HEPIA
HES-SO	University of Applied Sciences and Art Western Switzerland
HTC	Hydrothermal Carbonization
HWP	Harvested Wood Products
ICROA	International Carbon Reduction and Offsetting Accreditation
ICVCM	Integrity Council for the Voluntary Carbon Market
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
IgCC	International Green Construction Code
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal rate of return
ITINERO	Funding programme of FOEN and SFOE under the Climate and Innovation Act
ITMO	Internationally Transferred Mitigation Outcome
IWB	Energy, water and telecommunications utility in Basel
JASM	Joint Activity Scenarios & Modelling
KIG	Federal Act on Climate Protection Goals, Innovation and Strengthening of Energy Security (Climate and Innovation Act)
KIV	Climate Protection Ordinance
KliK	Foundation for Climate Protection and CO2 Compensation

KSpTG	Kohlendioxid-Speicherungs- und -Transportgesetz (German CO2 Storage and Transport Act)
KVA	Kehrichtverbrennungsanlage (waste incineration plant, see WIP/WtE)
LCA	Lifecycle assessment; Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product or service throughout its lifecycle.
LCOC	Levelized cost of capture
L-DAC	Liquid Direct Air Capture
LEED	Leadership in Energy and Environmental Design Program
LHV	Lower Heating Value
LULUCF	Land use, land-use change and forestry
MFH	Multi-family houses (Apartment blocks)
MOP	Maximum operating pressure
MRV	Monitoring, Reporting and Verification
NAGRA	Nationale Genossenschaft für die Lagerung radioaktiver Abfälle
NDC	Nationally Determined Contribution to the global effort to reduce GHG emissions under the Paris Agreement
NET	Negative Emission Technology (KIG Art. 2): biological and technical processes to remove CO2 from the atmosphere and bind it permanently in forests, soils, wood products or other carbon reservoirs.
NOAK	Nth-of-a-kind (plant)
NPV	Net present value
NZE	Net Zero Emissions by 2050 Scenario (IEA)
O&M	Operation and maintenance
OGE	Open Grid Europe
OPEX	Operational expenditures
PACM	Paris Agreement Crediting Mechanism
PAHs	Polycyclic aromatic hydrocarbons
PCI	Projects of Common Interest
PE	Partial equilibrium
PEFC	Program for Endorsement of Forest Certification
PFAS	Per- and polyfluoroalkyl substances
PPA	Power purchase agreement
PPP	Public-private partnership
PSA	Pressure swing adsorption
PSI	Paul Scherrer Institute
PtG	Power-to-Gas
PtX	Power-to-X
PV	Photovoltaic
PyCCS	Pyrolysis Carbon Capture and Storage
SAF	Sustainable aviation fuels
SAIPEM	Saipem S.p.A. (engineering contractor)
SBB	Schweizerische Bundesbahnen (Swiss Federal Railways)
SBRN	Swiss Biochar Research Network
S-DAC	Solid Direct Air Capture
SES	Swiss Energyscope (see SES-ETH)
SES-ETH	Swiss Energyscope – ETH model
SFOE	Swiss Federal Office of Energy
SIA	Schweizerischer Ingenieur- und Architektenverein (Swiss Society of Engineers and Architects)
SRL	Social Readiness Levels
STEM	Swiss TIMES Energy Systems Model
STRATOS	Direct air capture facility of 1PointFive, Ector County, Texas
SWEET	SWiss Energy research for the Energy Transition (SFOE programme)
TCCS	Timber Carbon Capture and Storage

TEN-E	Trans-European Networks for Energy
TES	TES Green Energy Hub, Wilhelmshaven
TF BSCR	Taskforce for Bio-based Solid Carbon Removal
TOC	Total organic carbon
ToT	Terms of trade
TRL	Technology Readiness Level
TSO	Transport system operator
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
UREK-S	Environment, Spatial Planning and Energy Committee of the Council of States
VBSA	Swiss Association of Municipal Solid Waste Incineration Plants
VCM	Voluntary Carbon Market
VCS	Verified Carbon Standard
WACC	Weighted Average Cost of Capital
WEF	World Economic Forum
WIP	Waste incineration plants
WtE	Waste-to-Energy plants
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research
WWTP	Wastewater treatment plant
ZHAW	Zurich University of Applied Sciences

1 Introduction

1.1 Background

The Swiss Climate and Innovation Act from 2022 (KIG) stipulates in its Article 3 that the Confederation shall ensure "that the impact of man-made greenhouse gas emissions in Switzerland is zero by 2050 (net-zero target)", whereby "(a) greenhouse gas emissions are to be reduced as far as possible; and b) the effect of remaining greenhouse gas emissions is to be offset through the use of negative emission technologies in Switzerland and abroad".

This specific wording of the law makes it clear that negative emission technologies (NET) are not seen as a substitute for reductions but should only be used for those emissions that cannot otherwise be avoided. This explicit clarification in the law is important, as otherwise the prospect of NETs would favour the continued use of fossil fuels and could reduce the pressure to reduce emissions. As this report will show, the costs of negative emissions are rather high and the potential for underground storage in Switzerland is limited, meaning that the use of negative emissions technologies is only an option for those emissions which are difficult to avoid and remain after emission reduction efforts and Carbon Capture and Storage have been applied where economically and technically feasible.

The focus of sub-project 3 of the project **De**carbonisation of **Cl**ties and **R**egions with **R**enewable g**A**ses (DeCIRRA) is not only on negative emissions, i.e., the removal of carbon from the atmosphere, but also on other carbon management approaches which include Carbon Capture and Utilisation/Storage (CCUS), i.e., the capture of CO_2 from point sources such as waste incineration plants and their subsequent storage (CCS) or utilisation (CCU). This means that CO_2 is almost completely removed from the exhaust gas, thereby either reducing emissions (when the carbon comes from fossil sources) or, in the case of capture from for example biomass combustion plants, negative emissions are generated by permanently storing the CO_2 that was previously absorbed by the biomass.

Negative emissions technologies are also known as Carbon Dioxide Removal (CDR) and include any deliberate human endeavour, technical or biogenic, to remove CO_2 emissions from the atmosphere and store them permanently. A good overview over 9 common CDR technologies is given by Minx et al. (2018). In the following report we will use the term **carbon management approaches (CMA)** to cover a variety of CCUS and CDR technologies, including NETs. Whether CCU and CCS can be considered CO_2-neutral depends very much on the product or storage facility, whether the CO_2 is stored and, if so, for how long (see Figure 5). What exactly is considered "permanent" has not yet been conclusively determined scientifically and politically at international level, but it can be assumed that permanent storage requires a storage period of more than 300 years (see, e.g., Matthews 2010). Currently, the political requirements in Switzerland are 30 years of storage (CO_2 Ordinance) and 100 years for international standards (Michaelowa et al. 2023). Under Article 6.4 of the Paris Agreement, there is no fixed definition of permanence. Rather, project methodologies are required to manage the risk of reversals (i.e. of a negative net change in GHG storage) through specific measures, including a reversal risk assessment and risk mitigation plan, post-crediting period monitoring and reporting, and the establishment of a Reversal Risk Buffer Pool Account. This buffer pool is fed with emission reduction/removal units (so-called A6.4ERs) based on the level of risk identified in the project's risk assessment and is replenished by the project participants after an event of avoidable reversals (UNFCCC 2024a).

The main difference between CCS and NET is therefore that the former prevents additional CO_2 emissions to the atmosphere, while the removal of CO_2 with NET relieves the earth's atmosphere, meaning that existing emissions can be offset to achieve the net zero target. NET can also help to achieve net negative emissions in the long term. Another difference is that emission reductions usually require a reference scenario or baseline to determine how high the reduction is. Such a baseline scenario can be established through a variety of methods, for example, by identifying how the heat or electricity would have otherwise been generated in the absence of the project. In the case of technical negative emissions, the baseline is easier to determine, as it can usually be assumed that no negative emissions would have occurred in the absence of climate policy. Because of this important difference, reductions and negative emissions are shown separately in the following report wherever possible.

Based on the 2050+ energy scenarios, the Swiss Federal Council (2022) has determined that to achieve its net-zero target, Switzerland would have to use NET to offset around 7 Mt CO_2 per year from agriculture, the waste sector and industry that are otherwise difficult to avoid. Of these, 2 Mt are planned domestically and a further 5 Mt abroad. An additional 5 Mt CO_2 would have to be stored with CCS as

emission reductions. This order of magnitude also results from other model calculations. For example, the SCCER Joint Activity Scenarios & Modelling (JASM) estimated a CCS volume of 10-20 Mt CO_2 per year by 2050 (Panos et al. 2021).

The aim of this synthesis report is to:

- summarise the state of knowledge of the research and implementation partners of DeCIRRA sub-project 3 and relevant external experts in the field of carbon management approaches,
- answer the research questions of DeCIRRA sub-project 3,
- identify gaps in knowledge and derive open research questions from this, and
- building on these, provide policy recommendations and an outlook for further research priorities in 2027-30.

Four different carbon management approaches will be comprehensively analysed as part of sub-project 3:

1. CO_2 storage in biochar and hydrochar,
2. CO_2 storage in construction timber, known as Timber Carbon Capture and Storage (TCCS),
3. bioenergy utilisation with CO_2 capture and storage (BECCS),
4. direct CO_2 removal from the atmosphere and storage (DACCS).

For the last two approaches, CO_2 transport with a focus on CO_2 pipelines and CO_2 storage are considered in separate sections, as they are important for both BECCS and DACCS and would otherwise have resulted in considerable repetition. The selection of the four approaches within sub-project 3 was based on the following criteria:

- High technology readiness level (TRL),
- Implementation partner in the DeCIRRA project with corresponding expertise,
- Relevant potential for Switzerland at home and/or abroad.

We acknowledge that additional carbon management approaches exist, such as reforestation and enhanced weathering – the latter already being the subject of ongoing projects in Switzerland (e.g. by Neustark). However, we consider their potential to be relatively limited in scope and therefore do not analyse them in detail.

1.2 Aim of SP3

The aim of SP3 is to estimate the **sustainably realisable potential** for carbon management approaches by taking technical, economic, and ecological criteria as well as social acceptance into account. To achieve this aim, the framework conditions that influence this potential are to be analysed, and policies that could be used to realise this potential are to be proposed.

In its report on the fulfilment of postulate 18.4211 Thorens Goumaz (Swiss Federal Council 2020), the Federal Council presented the following procedure for classifying sustainable and realisable potential. Figure 1 illustrates the various ways in which negative emissions are categorised. The Federal Council distinguishes between the theoretical potential ("Within the limits of physics and chemistry ..."), the technical potential ("According to the current state of research ..."), the economic potential ("Based on the economic and regulatory framework ..."), the ecological potential ("Without harming ecosystems ...") and the social potential ("What is socially accepted ..."). This results in "the sustainably realisable potential, which can, however, change over time – for example, depending on technical, economic and social developments" (Swiss Federal Council 2020, p. 13).

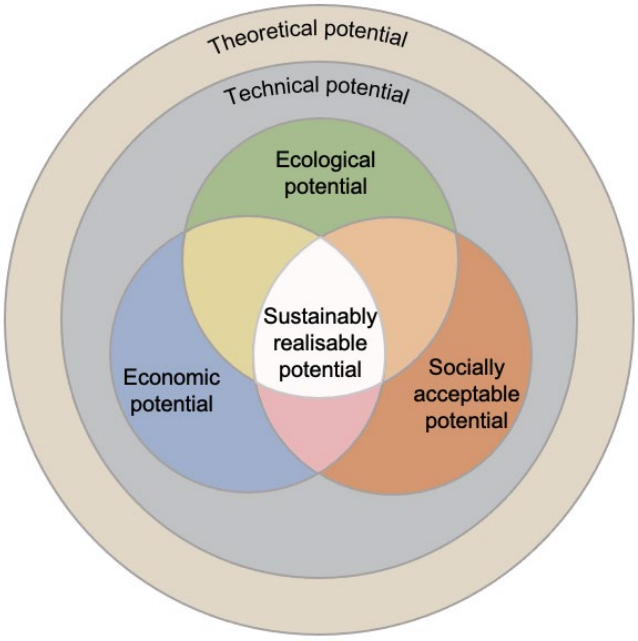


Figure 1: Definition of the sustainably realisable potential (Swiss Federal Council 2020).

This potential will be estimated by answering the following main research questions:

A Technological and economic potential:

1. What is the most efficient solution, when taking the international developments with regard to CO_2 storage and H_2 import into account for
    a. **combination** of the four assessed carbon management approaches,
    b. **timing** of investments?
2. Which **stakeholders** must be involved in planning and implementing different carbon management approaches (CMA) including the required infrastructure in order to achieve successful financing and communication in Switzerland?
3. Which **accounting and implementation frameworks exist nationally and internationally** to support the investments and what amendments need to be made in order to incentivise investments in CMA in Switzerland taking into account double counting and non-permanence risks as well as uncertainties regarding leakage?
4. Which **policies and revenue streams** (e.g., via selling of allowances or offsets) are currently available for the different CMA and what gaps and obstacles exist and could be filled by additional regulations to achieve viable **business models** and investments for efficient CMA mixes?

B Environmental potential:

5. How will **co-benefits** (e.g., enhanced soils from biochar), **external costs** (e.g., due to land and water use) and approaches to reduce risk (e.g., insurance) be taken into account in the investment analysis?

C Social potential:

6. Which CO_2 transport options are **supported by the general public** in Switzerland and how might various policies affect their **distributional impacts**?

1.3 Scope and structure of the synthesis report

The synthesis report aims to summarise the status-quo of the research questions listed above.

For each carbon management approach several aspects will be examined, including a) technology (e.g. costs, potentials and co-benefits/co-risks), b) accounting, c) actor mapping, d) policy screening, and e) business models.

Technology: For the four identified CMAs, the report starts with a general description including relevant technical and financial information (investment and operation cost) mainly based on existing literature, and establishes the relevant system boundaries, material and emissions flows. For TCCS, the additional

costs of wood construction compared to conventional buildings are used and for DACCS a full cost approach is used. As char and BECCS produce different products/services like electricity and/or heat or biochar itself in addition to the captured CO_2, different approaches are discussed about how the costs can be allocated between those products and the CO_2 removal and/or reduction.

The analysis also identifies potential co-benefits and external costs and risks like negative environmental side-effects as well as investment barriers and risks the CMAs may face.

The estimated costs and potentials and the corresponding drivers are further discussed for each technology. On the basis of four scenarios about potential future developments of the Swiss society and economy (see Guidati et al. 2024), the expected future role of each CMA for meeting Switzerland's net-zero target is modelled and discussed.

Accounting: The report examines three forms of accounting (see Table 1 and Section 5.3) and the differences are important to understand as they have implications on investment incentives for investors, environmental integrity and the tracking and quantification of expected and achieved mitigation results: 1) accounting in national greenhouse gas (GHG) inventories, 2) Project-based assessment using Life Cycle Assessment (LCA), and 3) mitigation strategies which are used in modelling and to quantify mitigation results in carbon markets (Geden et al. 2026). While national inventory approaches focus on annual fluxes – either positive or negative – and project-based approaches focus on emissions and removals across the lifecycle of a given project, we use the third form in our modelling of scenarios which assess the contribution of a given removal activity to an intended overall climate change mitigation strategy.

Table 1: Distinguishing the different accounting approaches (Geden et al. 2026).

	Objective and governance context	**System boundaries**	**Temporal scope**
National inventories	Reporting total GHG emissions and removals by sector in a given time period	Emissions and removals occurring within national borders, allocated to the sector in which they occur directly	Emissions and removals reported as a time series (usually annual)
Project-based assessments/LCA	Measuring the overall GHG balance of a project (LCA)	Emissions and removals pertaining to the project lifecycle, across sectors and national borders	Emissions and removals integrated over the project's entire lifecycle
Mitigation strategies	Planning for CDR activities as part of a portfolio of measures to meet an emissions target or climate objective	Emissions and removals as part of a mitigation strategy; system boundaries usually wider than inventories but narrower than lifecycle assessments	Emissions and removals integrated over the whole span of the planned activity for each method

In the context of national GHG **inventories** under the Kyoto Protocol or Paris Agreement, accounting has a different and very particular meaning. Understanding the accounting rules under the Kyoto Protocol and Paris Agreement in national inventories allows deriving incentives for countries to support specific carbon management activities. Reporting for emissions reductions and removals by sinks under national inventories is guided by IPCC guidelines and all Parties to the UN Framework Convention on Climate Change (UNFCCC) are obliged to follow these and produce regularly updated inventories of their GHG flows. However, what is reported does not mean that it can be accounted for compliance. For example, under the Kyoto Protocol harvested wood products (HWP) were reported in a specific line of the inventory but could not be accounted for compliance. Only Removal Units generated according to Article 3.4 and 3.5 under the Kyoto Protocol were able to be used for compliance. Under the Paris

Agreement, countries can account for HWP in their NDCs and they are free to choose between several approaches. This creates inconsistency across countries and raises a genuine risk of double-counting or non-counting, especially when the CMA involves transport of biomass (by way of a harvested wood product) across borders. If for example the CO_2 is biologically sequestered in one country (through biomass growth) and then processed into biochar which is applied to the soil in another country, the precise chain of accounting steps requires some degree of further clarification and specification of IPCC guidance, which is currently developed and publication is foreseen end of 2027.

LCA helps to make better decisions when comparing different project options. It can be used to better understand the expected material and emissions flows of specific value-chains and in particular to calculate the expected mitigation result as a CO_2 removal or a relative reduction in CO_2e emissions. LCA as a discipline allows taking into account associated emissions upstream and downstream including those occurring outside of Switzerland. It thus allows to directly compare the environmental performance of different CDR options. LCA requires selecting an appropriate system boundary to characterise an activity and clarifying the allocation of emissions reductions and removals to specific products in case of a process resulting in multiple products at once (e.g., pyrolysis used to produce biochar, heat, and potentially bio-oil byproducts).

In the context of **carbon markets** (e.g., those created under Article 6 of the Paris Agreement or voluntary carbon markets) the term accounting is sometimes also used to refer to the setting of a baseline and the monitoring, reporting and verification (MRV) of actually achieved emissions reductions or removals flowing from a particular project activity. Each carbon market is subject to a particular standard, which includes a set of specific methodologies that are to be used to make these calculations in order for a project to achieve mitigation results that can be traded as carbon market credits (in case of Article 6.2 these are called “internationally transferred mitigation outcomes” or ITMOs; under the Article 6.4 Paris Agreement Crediting Mechanism (PACM) they are called “Article 6.4 emission reductions” or A6.4ERs). Hence, accounting here also provides information on the incentives to invest in certain CMA projects.

Actor mapping: Actors for each of the CMAs were identified and structured according to their role. This allowed the development of a comprehensive **actors’ map** (see Section 3.1). This allows us to understand who are the stakeholders and groups that are relevant for implementing each of the CMAs (see Section 5.2).

Policy screening: For each of the CMAs a screening of existing policies and regulations in Switzerland and across the world to support the deployment of the analysed options is included. These are evaluated qualitatively on the basis of available information and existing literature. A stakeholder survey, furthermore, offers additional insight into policy preferences and opportunities (see Section 1.4.2 introducing the survey and Section 3.3 with the results). The policies and regulations are mapped to different types (e.g. markets, standards) and evaluated along a set of criteria (e.g. efficiency, effectiveness).

Business models: Business models were analysed in general and also for each technology separately. We also extended the research into the neighbouring EU region to gain an overview and a comparison with Switzerland. The introduction to the business models is in Section 1.7 and then technology-specific results are presented in each of the technology sections and at the end of the report in Section 3.5.

The key messages and policy recommendations derived from the analysis are presented in Sections 5 and 6. They include insights gained from the DeCIRRA Workshops and conferences.

1.4 Processes and methods

To answer the above-mentioned research questions, we have applied diverse scientific methods and established various processes for knowledge exchange, which are described in more detail in the following subsections. A first interim synthesis report was published in 2023, and parts of the present report build on it. The author and reviewer list has been adjusted accordingly: it names those whose contributions to the interim report remain substantively present in this version, rather than all of its original authors.

This report is the result of a collaborative effort involving authors and reviewers from a range of disciplines. Each contributor was engaged for their specific area of expertise and contributed to, or reviewed, only those sections falling within that area (see Details after the title page). Accordingly,

neither the authors nor the reviewers are responsible for the report as a whole, nor for statements, findings, or conclusions outside their respective fields of expertise. When reviewers disagreed with statements and assessments made in the report, we have tried to note this accordingly. Responsibility for the overall content, structure, and coherence of the report rests with the editorial team.

1.4.1 Knowledge building and exchange processes

The DeCIRRA SP3 consortium consists of four research institutions (ZHAW, PSI, ETHZ, Perspectives) and more than 15 implementation partners (new members have joined the project after the start). The following processes were used to ensure the exchange of knowledge between the various partners within the project and with external experts:

- Expert discussions/Expert groups

The scientific project partners held various technical discussions with individual implementation partners and experts outside the project. Over the course of the project, four expert groups were formed (on Biochar/BiCRS/PyrCCUS, TCCS, BE(CCS) and CCTUS). Major contributors who are not already listed as authors or reviewers are acknowledged in this report as experts (see "Members of expert groups contributing to discussions" following the title page).
The technical discussions with the project partners comprised clarifying mutual expectations within the project and the collaboration, building mutual understanding, and exchanging knowledge.

- Thematic workshops
    - Workshops were held online and in some cases on site to network, develop and consolidate knowledge on specific topics.
        - ➢ Internal workshops with the DeCIRRA partners on individual topics
        - ➢ External workshops that were open to other stakeholders or were held at public events.
- Knowledge processing
    - Miro boards[2] or white boards were used both within the workshops and for further collaboration on specific topics; the information collected was photographed and saved.
- Knowledge exchange
    - A joint literature database has been set up with Zotero.[3]
    - An Excel file with information on relevant stakeholders and projects was developed and was updated on an ongoing basis.
    - A shared One-Drive was created, although not all partners were able to access it.
    - Some of the files and data that need to be accessible to everyone were stored on google drive so that they can be worked on together.
    - Workshop results were shared directly on the Miro platform, and minutes were created and made available to the participants.

To support knowledge development, Master's and Bachelor's theses were advertised and supervised each year within the project.

The following Master theses were completed as part of this project:

- 2022: Life Cycle Assessment of Biochar to Soil Systems: A Parametric Analysis. Master thesis ETHZ, Gudrun Hoeskuldsdottir.
- 2022: Challenges and Opportunities for Biochar and Mass Timber Constructions as NETs in Switzerland, by Sofia Cafaggi. Here the focus was on the biochar and timber industry actors and their basic needs and opinions.
- 2022: Carbon Capture Storage (CCS) and Utilization (CCU) for Switzerland's Path to Net Zero, by Cedric Tanner. Here the focus was on CCS / U actors and possible business models.
- 2023: Negative Emission Technologies: Swiss Actor Network and Attitudes towards Policies, by Luca Dittli, with a focus on actor mapping of the entire NET network and attitudes towards policies. A large survey was conducted as part of this master's thesis.

The following Bachelor theses were completed as part of this project:

- 2022: Public perception of negative emissions technologies in Switzerland - An analysis based on a quantitative survey, by Daria Sutter.
- 2023: The media discourse on negative emission technologies (NET) in Switzerland, by Maurin Forster.
- 2024: Emissions Avoidance Credits versus Emissions Removals Credits. by Tobias Grütter.

[2] https://miro.com/
[3] https://www.zotero.org/

- 2025: Skalierung für den Klimaschutz: Business Modelle von Negativen Emissionstechnologien by Jonas Lagler.
- 2025: Hydrochar als Klimamassnahme? Stakeholder Perspektiven zur Einlagerung in der Schweiz by Flurin Pfalzgraf (Beste Bachelorarbeit in Betriebsökonomie, ZHAW).

1.4.2 Scientific methods applied

The following scientific methods have been applied to obtain further information:

- Literature research
    - The Zotero software was used in the project, which allows all project members to enter literature collaboratively into the same database, which can then be cited directly in project reports and publications. In the course of the project's 4 years, over 700 publications were viewed and classified.

- Two models were applied
    - The Swiss Energyscope model, an energy-system model maintained at ETH (SES-ETH), which determines the investment and operation strategies that minimize the total annual cost of the Swiss energy system, given the end-use energy demand, the efficiency and costs of the conversion technologies, and the availability and costs of the energy resources. See Scenario report (Guidati et al. 2024) for more details and assumptions for scenarios in Section 1.5.
    - GEMENE, a small-open-economy computable general equilibrium (CGE) model, was tight coupled to the SES-ETH model. GEMENE is calibrated to the 2014 Energy Input–Output table (NAMEA) and projected forward to 2050. It distinguishes about 30 economic sectors, five household income quintiles, government, and investment. See Working Paper Landis 2026 for more details.
- Surveys
    - A representative survey in the Swiss German part of Switzerland with more than 3,000 participants was conducted in November 2025. In terms of gender and age, the survey was representative of German-speaking Switzerland. The survey assessed climate change and CCTS knowledge levels, environmental behaviour and attitudes and socio economics variables. The core of the survey was a randomised experiment in which participants were randomly assigned to one of three CO_2 transport options (transport via pipeline, train or truck). The three options were further differentiated by information if the pipeline is repurposed or new or by different information on safety standards for the road and train transportation options. See the working paper by Boogen et al. (2026) for more details.
    - Before the representative survey, a survey was sent to approximately 12,000 ZHAW students as part of Daria Sutter's bachelor's thesis. About 300 students completed the questionnaire, who were asked about their level of knowledge of NET and the acceptance of various NET approaches.
    - As part of the Master's thesis "Negative Emission Technologies: Swiss Actor Network and Attitudes to Policies", a large stakeholder survey was conducted among all NET actors in Switzerland. The results were analysed in the master's thesis and have been incorporated into this report.
- Interviews
    - Many qualitative interviews were conducted with NET experts as part of the master's and bachelor's theses. These were recorded, transcribed and can be found in the master's and bachelor's theses.
- Text data analysis
    - As part of Maurin Forster's Bachelor's thesis, the portrayal of NET approaches in Swiss print media was analysed, with 115 newspaper articles being quantitatively and qualitatively evaluated.

1.4.3 Meetings and events

Within and around the DeCIRRA SP3 project more than 40 events, meetings and workshops took place. In addition, the results have already been presented several external conferences (e.g. Disentis Energieforschungsgespräche, SSH ETH and Uptake Milano). We also established a regular online marketplace for project partners and guests, which took place since 2024/25 almost every Tuesday at

lunchtime to present recent results from the DeCIRRA or other fitting project. Every Friday morning a management board meeting took place. You can find a detailed table with all the special DeCIRRA – mainly SP3 - organised events in Appendix 1.

1.4.4 Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Claude for translation and to improve readability and language of parts of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

1.5 Introduction to scenarios

To assess the most cost-efficient combination of carbon management approaches (CCUS, NETs) under varying domestic and international conditions – including CO_2 storage access and use of international offsets – the following four contrasting scenarios for Swiss decarbonisation by 2050 were developed (see Guidati et al. 2024 for more details):

Octopus (High innovation, open markets, international cooperation): Switzerland leverages the full range of carbon management approaches, supported by heavy initial subsidies. International offsets combined with pipeline access to CO_2 storage abroad enable Switzerland to achieve its net-zero target and position itself as a global climate leader.

Butterfly (High innovation, domestic focus): Similar technology push as Octopus, but strong political opposition limits reliance on international offsets. Switzerland meets its net-zero target largely through domestic efforts, with SAFs and CO_2 storage abroad as the main exceptions.

Clam (Low innovation, limited international cooperation): Hesitant investment in CMA and failed EU cooperation on CO_2 transport and storage leave Switzerland unable to realistically meet its 2050 climate target at politically acceptable costs, generating significant reputational burden.

Snail (Late acceleration, medium constraints, international cooperation): Switzerland starts slowly but accelerates from the mid-2030s. Net-zero is just within reach by 2050, but at substantially elevated cost due to delayed action which results in higher transport and abroad storage costs and late-stage reliance on international offsets.

Table 2: Key modelling assumptions for the four scenarios.

Narrative	 Octopus	 Butterfly	 Clam	 Snail
Domestic emissions in 2050: to be compensated with international offsets	6 Mt CO_2e/year	0 Mt CO_2e/year	0 Mt CO_2e/year	6 Mt CO_2e/year
Cost of CO_2 transport and storage abroad	100 – 200 CHF/tCO_2	100 – 200 CHF/tCO_2	800 – 1,600 CHF/tCO_2	400 – 800 CHF/tCO_2
Limit to timber storage (TCCS)	2 Mt CO_2/year	2 Mt CO_2/year	2 Mt CO_2/year	2 Mt CO_2/year
Limit to biochar use	5 Mt CO_2/year	5 Mt CO_2/year	5 Mt CO_2/year	5 Mt CO_2/year
Innovation	Innovative	Innovative	Conservative	Conservative
Market access	Together	Together	Alone	Together

We implement those scenarios with the Swiss Energyscope model. Several elements have been added or remodelled compared to the former results published in the Scenario report (Guidati et al. 2024), though the core assumptions (see Table 2) underlying the four scenarios remain unchanged: transport costs, maximum timber construction shares, and biomass assumptions are the same as before. For timber storage (TCCS) has been conservatively set at 2 Mt CO_2/year, which includes imported wood. This estimate is consistent with Priore et al. (2025), whose modelling puts annual biogenic carbon storage in Swiss buildings at up to 2.5 Mt CO_2 by 2050. Their scope is broader, as it includes both structural timber and non-structural bio-based materials such as straw, grass, hemp and wood-fibre insulation as well as wood-based finishings.

The main model updates are:

1. **Supply security** has been introduced via parallel optimisation, averaging across multiple years and weighting by probability. This may generate higher domestic demand for electricity and heat than in the previous version.
2. The **electricity sector** is now modelled with greater temporal resolution, using a seasonal distribution across the year. This allows for cheap electricity imports in summer and exports in winter. The surplus summer electricity also allows, if optimal, that hydrogen is produced via electrolysis in Switzerland.
3. **Biomass-to-biochar conversion efficiency** has been reduced, reflecting lower biochar yields per unit of biomass, assuming that not all pyrolysis plants are optimising for biochar but may also produce combined heat and power and other byproducts. In addition, pyrolysis plants are now permitted to incorporate CO_2 capture.
4. **Hydrochar** has been added as a technology. Unlike biochar – where operators receive a payment for the biochar itself – hydrochar storage must be paid for. As a result, hydrochar capacity is only built out in scenarios that already feature higher marginal CO_2 removal costs.
5. **Sustainable fuels (SF)** are now modelled explicitly, including sustainable diesel, which is demanded and imported by the transport sector. An import ratio of 1 (sustainable diesel) : 4 (sustainable aviation fuel) is assumed and it may be that in some scenarios there is more SAF imported than previously when this was exogenously determined at the 70% SAF and 30% fossil kerosene reflecting the blending requirement in 2050.

1.6 Introduction to survey experiment on public perception of CO_2 infrastructure

A representative online survey was conducted in November 2025 following consultation with DeCIRRA experts in summer 2025. The aim of the survey experiment was to assess public perception, knowledge, and opinions on carbon capture, transport, and storage (CCTS) technologies in Switzerland. The survey measured climate change and CCTS knowledge, environmental attitudes and behaviour, and socioeconomic variables. The core was a randomised experiment assigning participants to one of six CO_2 transport scenarios, each with a different transport approach, safety information, an explanatory text tracing the process from capture at a waste-to-energy plant to permanent storage, and an illustrative icon (see Figure 2). Half of respondents additionally received context noting that current Swiss CO_2 transport volumes represent only 1% of projected future volumes. Participants then rated their assigned scenario on first impressions, support, emotional reactions, and perceived usefulness, safety, and fairness.

The survey also assessed attitudes toward permanent carbon storage. Respondents first indicated whether they agreed that domestic CO_2 storage should take place in Switzerland if safely feasible. They then rated their intuitive comfort with four storage methods on a five-point scale from 1 (very uncomfortable) to 5 (very comfortable):

- CO_2 stored as a gas under high pressure deep underground ("Als Gas in grössten Tiefen in den Boden gepresst")
- building on these, provide policy recommendations and an outlook for further research priorities in 2027-30.
- Solid plant-based carbon (biochar) stored underground, e.g. in disused gravel pits ("Feste Pflanzenkohle unterirdisch, z.B. in alten Kiesgruben gelagert")
- Carbon bound in concrete granulate and reused in buildings ("Gebunden in Betongranulat, das wieder in Gebäude eingesetzt werden").

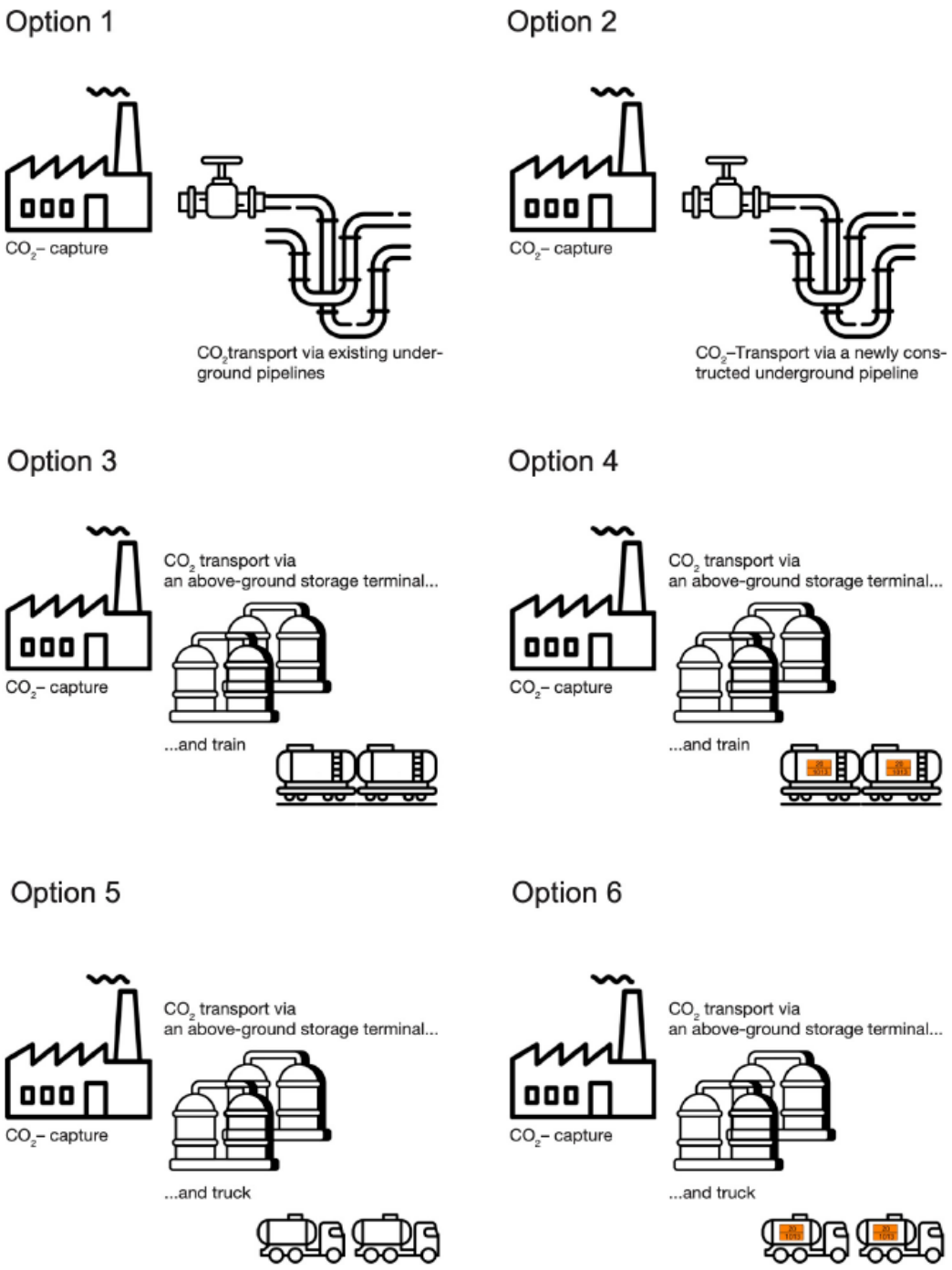


Figure 2: CO_2 transport scenarios introduced in survey experiment.

The survey used the German term *Pflanzenkohle* (plant coal) for all solid biomass-derived carbon, a choice made deliberately for comprehensibility: the term accurately describes both pyrolysis-based biochar and hydrochar as carbonised plant material, while technically precise alternatives such as *Hydrochar* would have been unfamiliar to most respondents. Responses therefore reflect public acceptance of the underlying storage concept (solid plant-derived carbon in a given context), which is the policy-relevant quantity of interest.

We received 3,058 responses from the German-speaking part of Switzerland and the sample is representative in gender and age. The gender split is almost equal, with 49.7% female respondents. Respondents range from 15 to 79 years, with an average age of 46.8 years. The vast majority hold Swiss nationality (92.0%). In terms of household composition, 42.1% are married, 65.9% are employed, and 50.2% own their home. Mean household size is 2.6 members, and 18.3% report having children under 18 in the household.

The sample is highly educated: 47.1% hold a university or higher vocational degree, 43.5% have upper-secondary qualifications, and 9.4% have no qualification beyond compulsory schooling. The sample skews toward middle-to-upper income households: one third report a gross household income above CHF 9,000 per month, while fewer than one in five earn below CHF 6,000.

The results of the survey experiment are summarised in Section 2.6.4 (risks related to transport and storage).

1.7 Introduction to business models

The DeCIRRA project also aims to understand the existing and possible business models for upscaling carbon management technologies, which strongly depend on incentives, barriers, support and regulatory conditions. The project team was supported by three Master and two Bachelor students who wrote their theses on the topics. Three expert workshops were also conducted on the subject. In this section we will briefly introduce the topic, then in each technology section the CMA-specific implications are described and finally the findings across technologies are summarised in Section 3.5.

Business models describe how a company creates, delivers, and captures value. According to Gassmann et al. (2013), pure product or technology innovation is no longer sufficient to secure a company's long-term survival – future competition will increasingly be fought between business models rather than between products alone.

Gassmann et al. operationalise the business model concept through what they call the "Magic Triangle" (see Figure 3), structured around four interdependent dimensions: **Who** (which customer segment is targeted), **What** (what value proposition is offered), **How** (how the value is created, including processes, resources, and capabilities), and **Value** (how revenue is generated and financial viability is secured). These dimensions are not independent; a viable business model requires internal consistency across all four.

A key insight from Gassmann et al. is that approximately 90% of successful new business models are not entirely novel inventions, but recombinations of existing patterns from other industries. On this basis, the authors identified 55 recurring business model patterns – such as Razor and Blade, Freemium, or Subscription – that can serve as templates for innovation. To develop new business models, they recommend first questioning the dominant logic of one's own industry, deliberately drawing inspiration from cross-industry examples, and testing assumptions early and iteratively against real customer feedback (Gassmann et al. 2013).

In the context of the DeCIRRA project, this framework served as the analytical foundation for examining how Carbon Management Approach providers structure their value creation and revenue logic, and where the key barriers to viable business model development currently lie.

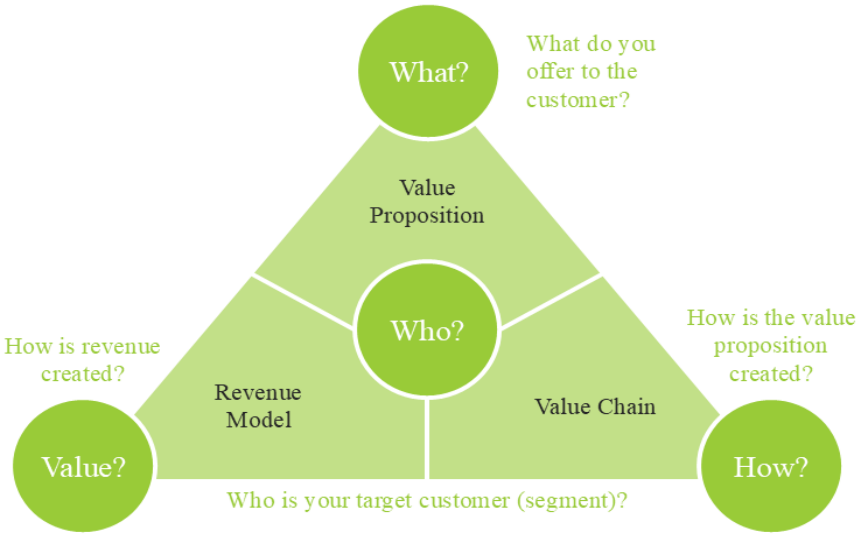


Figure 3: The Magic Triangle (Gassmann et al. 2013).

Readiness level for scaling

The Technology Readiness Level (**TRL**) is an established assessment framework for determining the technological maturity of innovations and it is used across industries as a tool in research and technology funding (Cames et al. 2023, p. 56; UNECE Task Force on Carbon Neutrality n.d., p. 14). The scale can be summarised in three phases: basic and applied research (TRL 1 to 3), technology development, piloting, and demonstration (TRL 4 to 6), and the subsequent advancement to full maturity (TRL 7 to 9).

But for a successful scaling of new technologies a high TRL is not sufficient, that is why the United Nations Economic Commission for Europe (UNECE) introduced two further metrics of the TRL-Logik (Gaido 2026):

- Commercial Readiness Levels (**CRL**): Assess commercial and market-specific indicators that go beyond technological maturity and are decisive for successful market introduction.
- Social Readiness Levels (**SRL**): Measure the extent to which new technologies are accepted by society, by individuals and groups, and whether they can be successfully integrated into regulatory and financial frameworks.

If these three dimensions are not synchronised, as shown in Figure 4, delays, additional costs, or outright failure of technology adoption result.

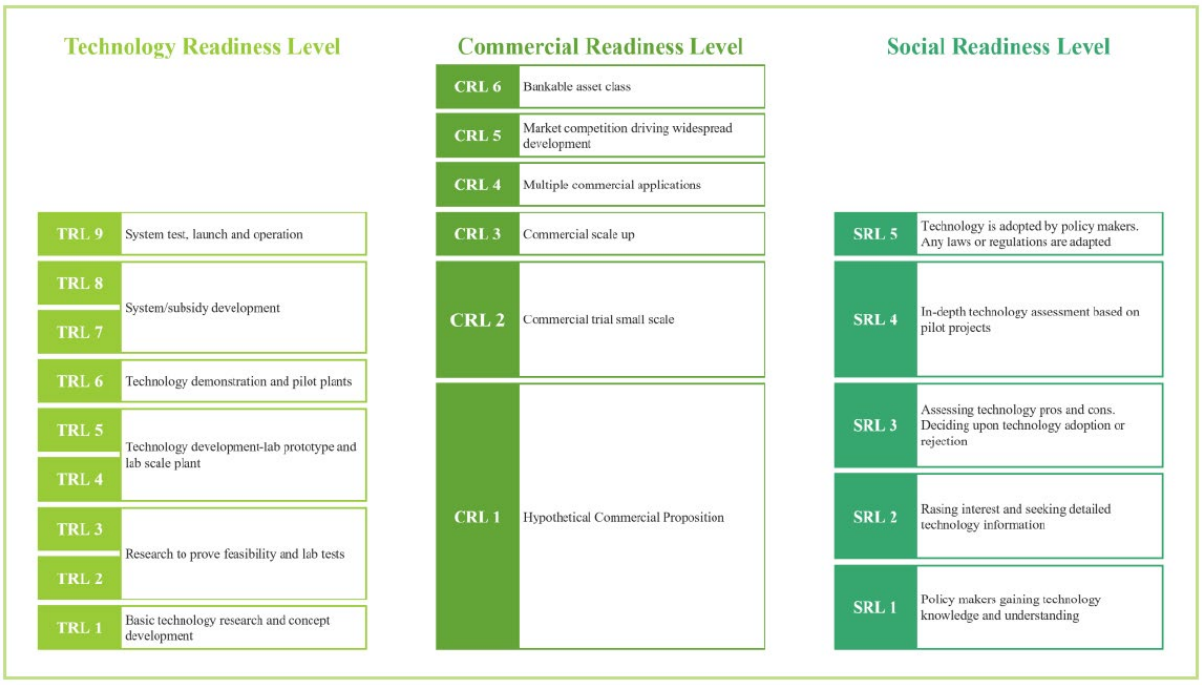


Figure 4: Technology, Commercial and Social Readiness Level (Gaido 2026).

2 Analysis of biological and technical CMAs

2.1 General introduction to CMA and system boundaries for quantification of emissions and other environmental burdens

Carbon management approaches (**CMA**) encompass both carbon dioxide removal (**CDR**; see Figure 5) and emissions reductions, covering the capture, transport, reuse, and storage of CO_2. Capturing of CO_2 from the atmosphere can happen directly from air (direct air carbon capture and storage **DACS**) or via biogenic processes.

Captured carbon can be stored in gaseous form underground. "Carbon Capture" ("CC" in the abbreviation of CCS or of BECCS) refers to various processes for capturing CO_2 from point sources. This report also considers three forms of biological carbon removal and (solid) storage (**BiCRS)**:

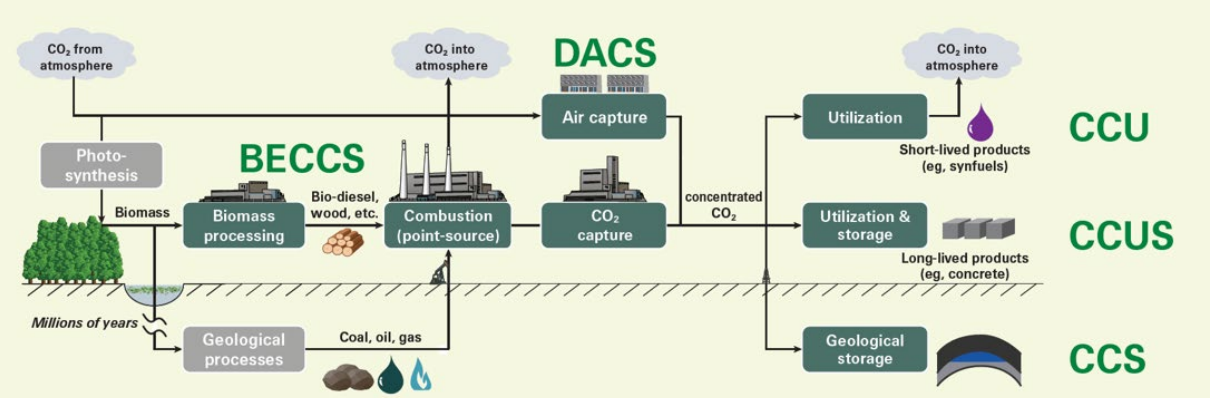
1. biochar carbon removal (BCR) (from pyrolysis),
2. hydrochar (from hydrothermal carbonization, HTC),
3. timber carbon capture and storage (**TCCS**).

If biomass (typically wood) is burned for energy and the CO_2 is captured and stored, this is termed **BECCS** (In EU regulation, the term BioCCS is used, which also covers CO_2 captured during bioethanol fermentation or biogas upgrading). The processes used not only differ in terms of technology, but also depend on the type of point source, e.g. the raw material and the utilisation of the CO_2. Negative emissions can only be achieved when biomass is used and not fossil fuels, otherwise the processes can be maximally climate-neutral ("carbon neutral") depending on their characteristics.

Possible point sources are exhaust gases from combustion or calcination, product gases from chemical reactions, cement production, reforming, pyrolysis and gasification as well as gas mixtures from biological processes (fermentation or anaerobic digestion). The composition of the source material of the point source is important for the assessment. In the case of biogenic carbon from biomass, plants have previously removed the carbon from the atmosphere, while fossil carbon comes from coal, crude oil or natural gas and geogenic carbon is released from the carbonate components of minerals, for example during cement production.

The actual separation of CO_2 can be carried out in many different ways, e.g., using scrubbers and adsorbers that utilise the solubility or polarity of the molecule, as well as membranes and condensation. Accordingly, the processes also differ in the operating conditions used (pressure, temperature), the capital costs and the energy balance (electricity, heat). Which of the separation processes is most suitable depends on the potential integration with existing process steps, particularly in the case of heat integration and recovery, and can vary depending on the location and size of the plant, which also explains the large number of established processes.

A distinction is made between the following cases for the use of the captured carbon dioxide (Figure 5): 1) Methods that fix the carbon for a long time, for example in aquifers, rocks or former oil and gas reservoirs, as well as carbonation of concrete granulate; 2) Uses for products with long duration such as biochar in concrete 3) Uses for products that are consumed again relatively soon, e.g., energy sources, chemicals, consumption goods. In the first case, we speak of "sequestration" or "storage" (**S**), in the second case of “use and storage” (**US**) and in the third case of "use" (**U**). This results in a total of six combinations and the corresponding abbreviations, of which only the sequestration of biogenic carbon can be considered a negative emission (BECCS, DACS and CCUS which includes BiRCS and TCCS). The (re)use of captured CO_2 (**CCU**) of fossil or geogenic carbon as a substitute for fossil fuels in applications that are difficult to defossilise, for example, increases the CO_2 concentration in the atmosphere and can only be seen as a transitional solution at best. **CCS** of fossil origin is also climate-neutral at best, as emissions, energy consumption, auxiliary materials and the environmental impact of the capture and conversion processes and CO_2 logistics must always be taken into account. In the long term, biomass will have to be used to produce everything that is currently obtained from fossil raw materials (CCU). For example, the CO_2 can be used directly in power-to-X processes with hydrogen to produce hydrocarbons that can be used as energy sources (methane, methanol, petrol, kerosene, diesel, paraffin) or chemical precursors (primarily methanol and other alcohols and ethers) and thus replace fossil products.



	Today	CCS	BECCS	DACS	CCU	CCUS
Main input	Fossil fuels	more fuel	Biomass (land, water, fertilizer)	Heat/power from renewables	Heat/power (from renewables)	Heat/power (from renewables)
Output	Heat/power, industrial products	Heat/power, industrial products	Heat/power, industrial products	–	Short-lived products	Long-lived products
CO_2 balance	Positive	Neutral	Negative	Negative	Positive for fossil CO_2 Neutral for bio/air CO_2	Neutral for fossil CO_2 Negative for bio/air CO_2

Source: Swiss Re

Figure 5: Classification of carbon management approaches based on the input and output (Source: SwissRe).

Even though specific CDR methods can substantially differ in their nature (Figure 6) (Cobo et al. 2023; Fuss et al. 2018; S. Smith et al. 2023), the quantification of their long-term effectiveness in terms of CO_2 removal from the atmosphere requires a comprehensive and consistent method for the accounting of GHG emissions (Brander et al. 2021; Terlouw, Bauer, et al. 2021).

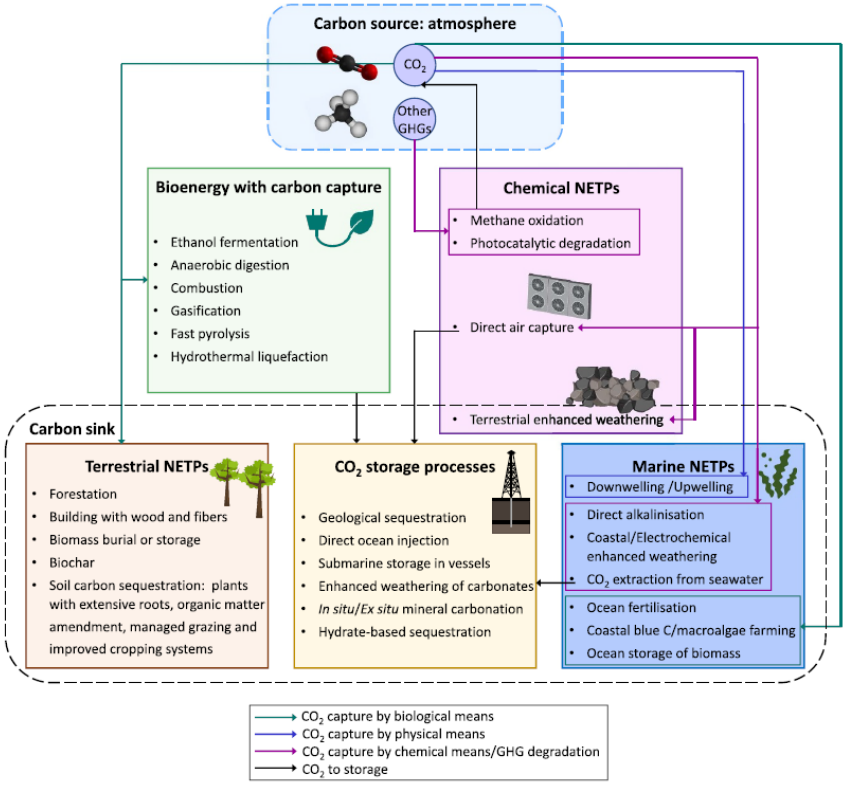


Figure 6: Overview of CDR methods and CO_2 sequestration processes (Cobo et al. 2023).

Environmental Life Cycle Assessment (LCA) can be considered as an appropriate method for this purpose and has been applied for the evaluation of CDR already (Goglio et al. 2020; Terlouw, Bauer, et al. 2021). Applying LCA to CDR is supposed to guarantee a comprehensive accounting for direct and indirect GHG and other emissions to the environment as well as resource consumption (e.g., in terms of land, water, minerals and metals) associated with any CDR method. System boundaries in the LCA context include the production, operation, and end of life of any product or service and all associated energy, material and resource flows as well as emissions to the environment (Hauschild et al. 2018). This includes the required infrastructure, the so-called “capital goods” (Frischknecht et al. 2007). Processes included directly in the production, operation, and end of life of any product or service represent the so-called “foreground system”, often referred to as “product system”. Processes linked to material and energy flows from and to these processes represent the so-called “background system”. This background system is – in terms of emission and resource consumption data, material and energy flows – covered by background databases such as the ecoinvent LCA database (Wernet et al. 2016).

In the context of CDR, **permanent** (or at least “long-term”) removal of CO_2 from the atmosphere represents the service a CDR method provides. A key issue in this context is the time period for which CO_2 is temporarily stored and removed from the atmosphere (so called **durability**) and the associated climate impact in terms of delayed atmospheric temperature increase. Ideally, this would be considered by means of dynamic accounting of carbon stocks and flows over time and quantifying associated climate impacts, e.g., in terms of modified global warming potential of CO_2 emissions shifted back in time (de Kleijne et al. 2022). However, existing approaches to integrating temporary CDR into climate policies have relied on equivalency assumptions between temporary and permanent CDR that contradict physical climate science, since temporary CDR cannot fully offset CO_2 emissions in the way permanent CDR can. Often it was assumed that CO_2 stored for 100 years or more was defined as "permanently removed" and assigned a global warming potential (GWP) and climate impact of zero (de Kleijne et al. 2022; Terlouw, Bauer, et al. 2021). This equivalency assumption, however, remains scientifically contested - especially in the context of carbon markets -, and ambiguity persists about the extent to which temporary CO_2 removal can be considered effective CDR and what climate benefits can legitimately be assigned to it. Two approaches are currently under discussion:

1. Gupton et al. (2026) propose a reversal risk-management framework for CDR, recommending that the binary "permanent" or "impermanent" labels be replaced with a continuous concept of durability. This more accurately reflects the dynamic nature of ecosystem carbon storage and accommodates nuances that the conventional notion of permanence – as widely applied in carbon markets – tends to obscure. They operationalise durability as a metric comprising two components:
   (1) the timeframe for which the credited CO_2 equivalent is held out of the atmosphere, and
   (2) the likelihood that it will remain stored for that timeframe, which corresponds to the reversal risk.
   To manage this risk, Gupton et al. identify seven methods ranging from risk-transfer strategies – such as buffer pools, insurance, and carbon trust funds – through purchasing strategies such as vertical and horizontal stacking, to accounting approaches including risk-weighted and time-weighted accounting.

2. He et al. (2026) take a different angle, focusing on the emission source being compensated. They argue for a like-for-like compensation principle, under which temporary CDR is appropriate for offsetting non-CO_2 climate forcers, particularly short-lived species, rather than being used interchangeably with permanent CDR.

Often, GHG emissions associated with direct and indirect energy (heat and/or electricity) consumption of CDR methods represent the most important sources of those and thus determine the “**net efficiency**” or “**net effectiveness**” (equivalent to the gross amount of CO_2 removed and permanently stored minus direct and indirect GHG emissions caused by a CDR method from an LCA perspective) of CDR. However, also land use and land use changes and associated climate impacts can play important roles, especially for CDR methods relying on biomass in one way or the other (S. Smith et al. 2023; Terlouw, Bauer, et al. 2021).

Since LCA does not only quantify GHG emissions and climate impacts, but a very broad range of environmental burdens due to pollutant emissions and resource needs, it can – to some extent – be used to quantify environmental **co-benefits and trade-offs** coming along with CO_2 removal (Cobo et al. 2022). These can refer to impacts on human health and ecosystems as well as resource scarcity and need to be evaluated before upscaling and large-scale implementation of CDR (Fuhrman et al. 2023; Strefler et al. 2021). Since such impacts, however, are often location-specific and life cycle impact assessment is usually performed in generic ways not taking into account location-specific boundary

conditions in terms of affected population or ecosystems, generic LCA results for burdens other than those on climate change need to be interpreted with caution. Case-specific assessments including other methods than LCA would be required. There are also potential side effects which cannot be analysed within the established LCA framework, e.g., location-specific modifications of soil quality due to biochar applications, impacts on the food system as an indirect effect of bioenergy related land use, and also social impacts (Bellamy & Geden 2019; Hasegawa et al. 2021).

Finally, any accounting needs to refer to a certain amount of product or service, in LCA terms the so-called “functional unit”. For CDR, this can be one unit of gross carbon dioxide removed from the atmosphere, which allows a comparison of different CDR methods (Terlouw, Bauer, et al. 2021). While allowing for a direct comparison of the environmental performance of different CDR options, this functional unit of “gross carbon dioxide removed” must somehow consider the fact that many CDR options provide goods or services in addition to CDR, for example providing construction materials in the case of wood as construction material (TCCS) and energy supply in the case of BECCS. In other words, CDR might not always be the primary driver for providing goods and services, but rather a co-benefit. This needs to be addressed in case-specific ways, which will be done in the following sections for each of the approaches.

2.2 Solid carbon removals – Biochar and hydrochar

2.2.1 General description

Biogenic char ("biochar" and “hydrochar”) is a stable, carbon-rich material made by heating biomass (e.g. woody residues, agricultural waste, sludge) between 150-800°C under the absence of oxygen. Because plants absorb CO_2 from the air while growing, turning that plant material into stable char effectively removes CO_2 from the atmosphere. Roughly 50% to 80% of the carbon in the original biomass ends up stored in the char, while the rest is turned into energy-rich bio-oil or -gas. Depending on the production process, char can be very stable and barely breaks down biologically or chemically. Made properly with certain quality control, biochar is currently mainly used for long-term storage in soil, where it acts both as a carbon sink and thanks to its porous structure and large surface area, also provides cobenefits: it can hold water and nutrients, which improves soil fertility, and it can reduce methane and nitrous oxide emissions from agriculture. These additional benefits are explained in more detail in Section 2.2.3.

If the biomass were left to decompose naturally instead of being turned into char, the carbon would simply return to the atmosphere through decomposition to CO_2 or even as methane. Converting it into biochar instead of letting it decompose is therefore a sensible way to keep that carbon stored in a stable form. Besides Biochar made via pyrolysis also hydrochar exists, which is made via hydrothermal carbonisation (HTC). These two production methods, and the resulting products, are explained below and in Box 1.

Production methods: Pyrolysis and HTC

Pyrolysis heats dry biomass to high temperatures (typically 375–800°C) in the absence of oxygen, causing it to release gases and leave behind a solid residue: biochar (Figure 7). There are three types: slow pyrolysis (slower heating, longer processing time, higher biochar yield), fast pyrolysis (faster heating, more bio-oil produced alongside the biochar), and gasification (a partial-combustion process that produces a gas mixture called syngas, with biochar as a by-product). Depending on the method used, focus can lie on the production of bio-oil, energy from burning syngas, or biochar yield, which have a large impact on how economically viable the process is. Which method makes the most sense depends on factors like the type and amount of feedstock available (e.g. forestry residues), what the biochar will be used for, and what infrastructure is available. for around 460 years (the so-called "half-life"), though the actual figure varies depending on the study, the production method, and the starting material.[4] Various biomass types can be used as **raw materials for biochar** production, which can be categorised into (a) woody and (b) non-woody biomass. Woody biomass includes trees and shrubs, etc., whereas non-woody biomass includes starch- or oil-containing biomass, such as energy crops (e.g., maize, wheat and sunflowers). Other substances cannot be categorised so clearly, e.g., liquid manure or solids from animals or human faeces (sewage sludge) and waste biomass consisting of different components. Minor plastic impurities or certain unmixed plastics can also be pyrolysed, but plastic mixtures, especially plastics with chlorine, such as PVC, lead to problematic by-products. The European Biochar Certificate publishes a positive list of authorised biomass raw materials for the production of biochar in the EU, which is also used in Switzerland (Carbon Standards International 2025).

HTC works differently: it processes biomass in water under high temperature and pressure, with limited oxygen, at relatively low temperatures (normally between 180-250°C). During this process, the biomass undergoes chemical reactions (hydrolysis, dehydration, polymerisation) and forms a solid, carbon-rich material called hydrochar. One advantage of HTC compared to pyrolysis is that it doesn't require feedstock to be dried first, so it can handle wet materials such as sewage sludge, food waste, and wet agricultural residues. Compared to pyrolysis, more carbon is retained and the actual energy needed to produce hydrochar is lower compared to biochar, but less energy-rich byproducts like bio-oil or syngas are formed and hence it requires energy input, while pyrolysis is self-sustaining. It is more tolerant of contaminants and in soil, hydrochar seems to be not as stable as biochar (Kambo & Dutta 2015; Masoumi et al. 2021; Ighalo et al. 2022; Cutz et al. 2025; Luo et al. 2025; Röhrdanz et al. 2019).

While biochar from pyrolysis is currently typically mixed into agricultural soil, hydrochar from HTC opens up a different storage option that has so far received little attention: Storing it permanently underground in geological formations, where it can keep carbon locked away for centuries (Sanei et al. 2024; Baars et al. 2026). This approach – removing and storing biomass-derived solid carbon rather than using it for

[4] https://biochar-international.org/

something else – is increasingly known as BiCRS (Biomass with Carbon Removal and Storage) (Guidati et al. 2024; Baars et al. 2026).

That said, HTC technology still faces hurdles before it can be rolled out commercially. The quality of hydrochar varies depending on what feedstock is used, and optimising the process is still a challenge. Investment costs remain high, and there are no standardised quality criteria yet for hydrochar products, which has slowed market adoption. Storing hydrochar in deep geological formations is considered safe and is already practiced in other countries, but in Switzerland regulatory hurdles currently stand in the way. Despite this, an industrial-scale production plant is planned at the Buchs wastewater treatment plant (Gautschi et al. 2024, 2026).

BOX 1: Comparison of HTC and Pyrolysis Processes, energy and mass balances

Step	Pyrolysis		HTC	
	General	Example *	General	Example *
1. Input	Dry biomass required(~10-15% moisture)	1000 kg biomass (50% wet)	Wet biomass fed directly	1000 kg biomass (50% wet)
2. Energy of Pre-treatment drying (Pyrolysis only)	-550 to -900 kWh per tonne water removed (drying)	- 350 kWh	Not applicable - The process works with wet biomasse	-
3. Process conditions	375 - 600 °C, dry, no pressure	500 kg dry biomass in reactor	normally 180-250 °C, pressurized water	500kg biomass + 500kg incl. water) + 2000kg processwater in reactor
4. Solid yield % of dry matter (kg)	~25-35%	30% = 150 kg Biochar	~35-72%	50% = 250 kg Hydrochar
5. Carbon content of solid	~60-85%	72% = 108 kg Carbon	~49-62%	55% = 137.5 kg Carbon
6. Energy of pyrolysis / carbonization process	+300 to +800 kWh / t dry feedstock (syngas/bio-oil surplus)	275 kWh	"Near self-sufficient" to -100 to -300 kWh / t dry feedstock	-100 kWh
7. Pressing & drying (HTC only)	Not applicable — biochar already exits the reactor largely dry	-	Mechanical pressing ~50-150 kWh/t + thermal drying (if needed) ~100-450 kWh/t	250 kg hydrochar x 0.3 kWh/kg = -75 kWh
8. Total net energy (row 2 + row 6 + row 7)	-300 to 125 kWh per tonne wet feedstock (rough estimate at 50% moisture)	-350 kWh + 275 kWh + 0 kWh = -75 kWh	-300 to -25 kWh per tonne wet feedstock (rough estimate, incl. pressing & drying, at 50% moisture)	0 kWh + -100 kWh + -75 kWh = -175 kWh
9. CO2e stored (per tonne DRY feedstock)	~ 0.55 – 1.09 t CO2e	0.4 t CO2e	~ 0.63 – 1.64 t CO2e	0.5 t CO2e
10. Output	Biochar	150 kg	Hydrochar	250 kg

• Own calculation and compilation. The general value ranges are drawn from various literature sources (Biochar International 2026; Ercan et al. 2023; Li & Jin 2025; Sivaprasad 2021); the example values in the 'Example' column are illustrative mid-point figures, not measured data from a specific source.

• CO_2e stored = carbon mass in solid product x 3.667 (CO_2/carbon molecular weight ratio, 44/12). This reflects gross carbon fixation only, before any permanence discount for long-term degradation.

• The calculation shows that very roughly 1 kg of dry biomass (100% dry) leads to 1 kg of CO_2 stored and ~2.5–3 t CO_2e per tonne of finished biochar/hydrochar

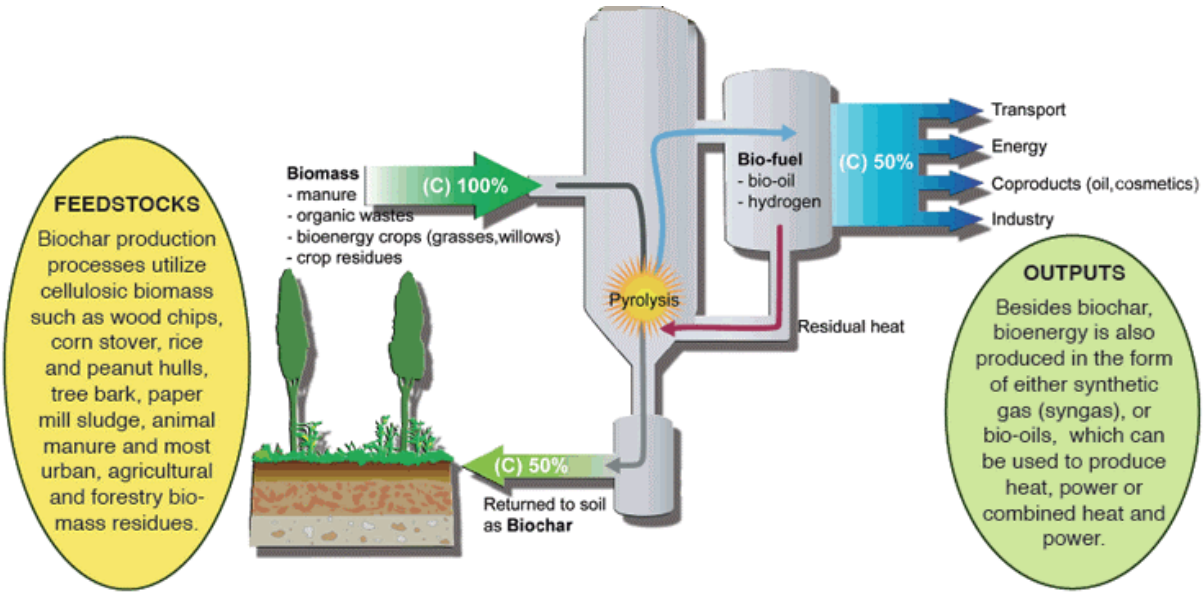


Figure 7: Biochar production via pyrolysis process (https://biochar-international.org/why-biochar/).

The **quality** of the char and therefore its application depends on many factors. The source material and the processing technology have a decisive influence on the quality and environmental impact of the product. There should be no harmful impurities such as heavy metals, pesticides or other chemical residues in the source material. If biochar is used for agricultural purposes and in the food chain, harmful polycyclic aromatic hydrocarbons (PAHs) must be avoided by using suitable input material and a constant and controlled process. The fulfilment of these requirements as well as of air pollution standards is guaranteed by well-known manufacturers; this cannot always be ensured by uncontrolled small plants. There are now also a number of pilot projects in the HTC area, where experience is being gathered on the quality of the hydrochar (Mehli et al. 2021).

Production / storage / applications of biochar

Biochar is used in various areas such as agriculture and urban development (e.g., as a soil improver), animal husbandry (as a feed additive and as a substitute for antibiotics), environmental technology (in wastewater treatment, e.g., to filter out microplastics), energy technology, as a construction material (e.g., for interior wall plastering) (Cames et al. 2023), as additive in the cement and steel industries, and even as a black colourant in the cosmetics and food industries.

Agricultural applications are either in animal husbandry or composting, where nutrients are released during biomass decomposition and hence biochar helps to stabilise these nutrients while reducing gaseous emissions. In detail, biochar is often loaded with nutrients by soaking it in liquid manure, or microbially activated with lactic acid or yeast bacteria. In this way, the soil, manure and feed processes can be optimised to not only add carbon to the soil, but other co-benefits can also be achieved.

Other important applications are in **landscape gardening**, where biochar is incorporated into the soil combined with compost or other fertiliser, while its sponge-like properties also make it suitable as a water-storing substrate for urban trees, all while creating a carbon sink in the soil.

Producers and technologies in the DACH region (Germany, Austria, Switzerland)

Biochar producers in the DACH region can be roughly divided into the following three categories (see Figure 8):

1. **Industrial, energy-led production process**: These companies focus on energy generation in the form of heat and electricity, with biochar as a time-variable by-product. These plants are usually electricity or heat-led with a correspondingly lower yield of biochar. The market leader for this technology is Syncraft. The major advantage of these plants is that they achieve good capacity utilisation throughout the year thanks to the three seasonally different and, to a limited extent, variable utilisation options, i.e., they do not generate large heat surpluses in summer, for example. The process is much more complicated and expensive and the biochar quality

(PAH issue) is not easy to control. Bioenergie Frauenfeld's wood-fired combined heat and power (CHP) plant is currently the only large-scale producer of biochar in Switzerland.

2. **Industrial, material-led production process**: These companies focus on the production of biochar, usually from low-grade forest residues or high-quality forest wood or agricultural residues. The process is material-led. The by-product is process heat, which can be used for the company's own process management (pre-drying of the biomass), electricity production, and in winter for local heating networks. Plant manufacturers include: CTS Carbon Technik Schuster, Biomacon, Pyreg and ETIA Ecotechnologies. Plant operators and biochar producers in Switzerland include Lignocarbon IWB and Inkoh.[5] The latest, so-called "fully integrated" plant is operated by Inkoh Lignocarbon, which offers ground, microbially activated biochar in addition to the usual, unground big bag charcoal
3. **Self-consumption by farmers**: Some farmers and cooperative associations produce biochar from their own raw materials, either for their own use and/or for sale to other farmers or garden centres in the region. Examples are: Verora and APD[6]. Both material-led and energy-led processes can be found. The latest developments are moving towards even smaller (farm) units, i.e. from Pyronet (www.pyronet.ch). Biochar quality is ensured when producers sell biochar to customers by following the biochar material certification of the European Biochar Certification by Carbon Standards International (CSI). These quality measures are also followed if a small producer is part of a carbon removal program following voluntary carbon market methodologies.

The category of manufacturer is largely dependent on the technology used. Below is an illustration from system manufacturer BIOMACON GmbH,[7] which categorises small systems (63 - 224 kW) for agricultural, municipal operations, forestry and greenhouses, and industrial systems (up to 500 kW) for sewage treatment plants, industrial operations and manufacturing processes or heat contractors.

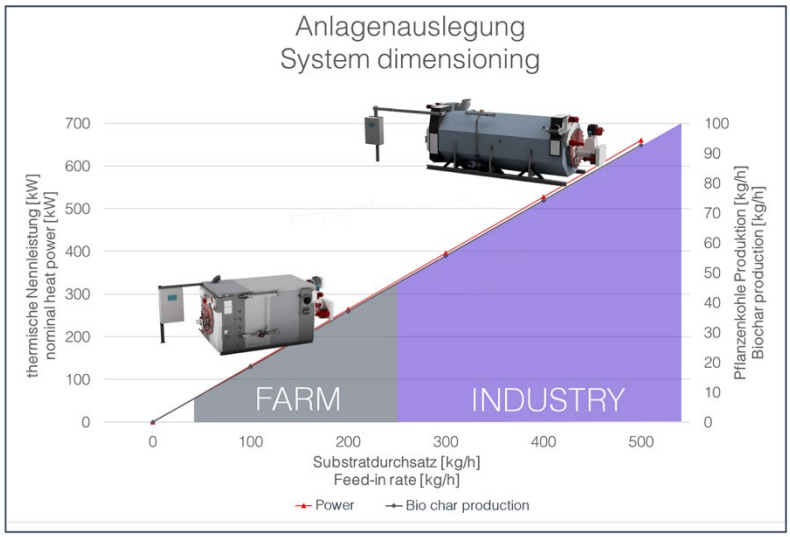


Figure 8: Biochar production plants (https://www.biomacon.com/).

Production / storage / application of hydrochar

HTC technology is technically quite mature, but the possibility to run industrial size plants depends heavily on the country and its regulation. Industrial-scale hydrothermal processing was already practised in the early twentieth century (Haubold-Rosar et al. 2016), and HTC plants are in commercial operation in the following countries: UK, Germany, Spain, Italy, Sweden, Belgium, Japan, China, USA and Mexico (Farru et al. 2024; Ho et al. 2024).

Switzerland has significant wet biomass potential, estimated at over 15 million tonnes annually (Thees et al. 2017), and the costs of HTC-based CDR are among the lowest of any technology-based option (Betz et al. 2023). Despite this, hydrochar storage is not mentioned in the EU Carbon Removals and Carbon Farming regulation, does not feature in Switzerland's CDR roadmap as an enumerated technology, and is absent from recent Swiss CDR scenario analyses (Guidati et al. 2024). Also a recent

[5] https://inkoh.swiss/
[6] http://www.verora.ch/, https://www.a-p-d.ch/pflanzenkohle/
[7] https://www.biomacon.com/

assessment of 14 German CDR options omits hydrochar (Borchers et al. 2024). It is, in short, a systematically underestimated option.

The reasons for this underestimation are mainly technical, but also governance-related, with open questions about long-term carbon stability and process water management (Luo et al. 2025). The management of HTC process water which contains elevated concentrations of organic compounds, nutrients, and potential contaminants represents a concrete technical challenge requiring regulatory attention and site-specific treatment solutions before storage can be scaled up (Ender et al. 2024). In Switzerland, existing waste legislation classifies stored hydrochar as waste, limits its landfill on grounds of organic carbon content (it could still be used as energy source) and contains no provision for a CDR-specific storage category.

A critical assessment of HTC upscaling and nine global commercialisation cases are presented in Ho et al. (2024). It is shown that the HTC process can be optimally integrated with biogas production and can generate other important biochemical base molecules.

2.2.2 System boundaries, material and emissions flows, and main drivers

Biochar production and various forms of its application can remove carbon dioxide from the atmosphere over long periods of time (i.e., “permanently”), as long as the carbon, originally embedded in biomass feedstock, which is converted to biochar (and co-products), remains in stable form in the biochar (or its form of application) and is not reconverted into CO_2 (or methane) and released back to the atmosphere.

The biochar product system includes the biomass supply chain, biomass conversion to produce biochar and co-products (usually, gaseous and liquid hydrocarbons), and biochar application. Depending on the application, specific side effects might take place – in case of biochar use as soil amendment in agriculture, such side effects include albedo changes of land surface, reduction of N_2O emissions from soils, and a potential increase in agricultural yields or reduced need for fertilisers. Most often, such side effects depend on local boundary conditions such as soil type or quality, which makes it hard to quantify them in generic or average ways.

Climate impacts associated with all the processes included need to be accounted for to quantify the CDR potential and effectiveness of biochar application. Emissions of other substances than GHGs and resource use need to be considered for the quantification of other environmental burdens than climate impacts. The provision of residual or waste biomass can be considered as “burden-free”, while environmental burdens of biomass production (including direct and indirect land use and associated climate impacts) must be taken into account in case of using dedicated crops or wood.

Accounting for climate impacts and other environmental burdens must take into account the multi-functionality of the biochar production processes (pyrolysis, gasification, torrefaction, hydrothermal carbonisation) or in other words, the fact that hydrocarbons, which represent useful products with a market value, are produced besides biochar. These hydrocarbons can be converted into heat and electricity, which are partially used for providing energy needed for feedstock drying and conversion. Surplus heat and electricity can be supplied to external users. Figure 9 shows an exemplary process system of biochar-to-soil application, including key processes and issues for carbon accounting and more general environmental assessment as well as potential side effects.

Multi-functionality of the biochar production process can be dealt with in different ways: One option is to allocate certain shares of the overall environmental burdens of the biomass-to-biochar production process and all processes prior to biomass conversion (e.g., biomass production and supply) to each of the co-products – either based on their energy content, their mass, or the economic revenue they generate; another option is to assume that co-products (here: surplus heat and electricity from conversion of hydrocarbons) substitute and therefore avoid other types of heat and electricity generation, for example marginal production technologies. Environmental burdens of substituted or avoided generation would be accounted for as environmental benefit, i.e., as credits with a negative sign, to be subtracted from the overall burdens of the biochar product system.

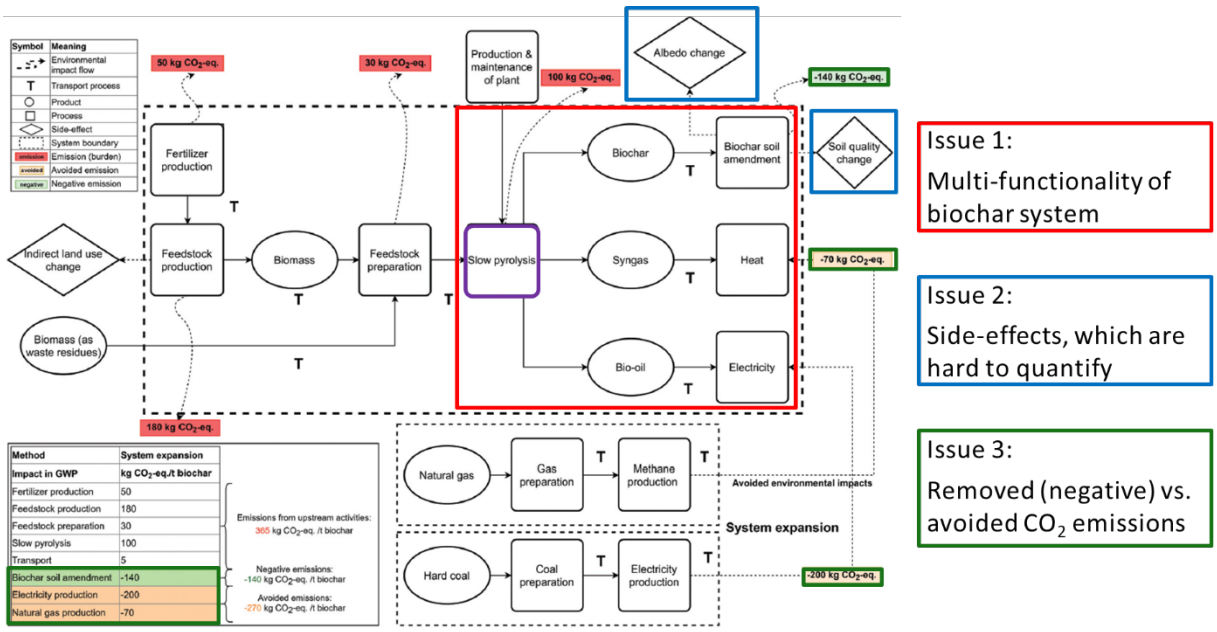


Figure 9: Exemplary process system of a typical biochar-to-soil process chain, visualising key issues in the (carbon) accounting; adapted from Terlouw et al. (2021).

Such avoided environmental burdens should always be reported separately from the carbon removal due to biochar production and application (Terlouw, Bauer, et al. 2021). This is particularly important for climate impacts mainly for two reasons: First, there is a fundamental difference between actively removing CO_2 from the atmosphere, which leads to a reduction of atmospheric temperature, versus reducing emissions from other sources, which "only" reduces further warming; second, avoided emissions/burdens always depend on a counterfactual or baseline assumption regarding the substituted products or services. This assumption depends on case-specific boundary conditions and might change over time, depending on the geographical area of interest. Most important in this context in terms of overall impacts on climate change are potentially substituted heat and electricity supply and their GHG emission intensities. Regarding the net effectiveness of carbon removal, the most critical factor is the fraction of carbon originally being present in the biomass and permanently staying in the soil (in case of the use of biochar as soil amendment), which depends on biomass type, pyrolysis technology and temperature as well as soil type and temperature.

In this part we focus on the specific facts for **hydrochar production**, based on a comprehensive paper by Mannarino (2022). LCA studies of HTC typically define **system boundaries** that begin at the feedstock collection or pre-treatment stage and extend through the HTC reactor itself, but the scope varies considerably depending on what downstream pathways are included (see Figure 10 for an example). At minimum, boundaries cover the HTC process unit and the separation of its outputs (hydrochar and process water). Many studies, however, expand the boundary further to capture how each output is subsequently valorised – for example, hydrochar combustion for energy, hydrochar use as a soil amendment, anaerobic digestion of the process water, or nutrient recovery steps. Because feedstock-specific upstream processes (e.g., sewage sludge collection and thickening at a wastewater treatment plant, versus collection of food waste or green waste) are also frequently included, comparing system boundaries across different HTC LCA studies is genuinely difficult: differences in operational HTC conditions, feedstock type, chosen valorisation pathway, underlying assumptions, and the exact point where the boundary is drawn all affect what is and isn't counted. Construction-phase impacts of the HTC plant itself are commonly excluded, on the grounds that they are relatively small compared to operational impacts.

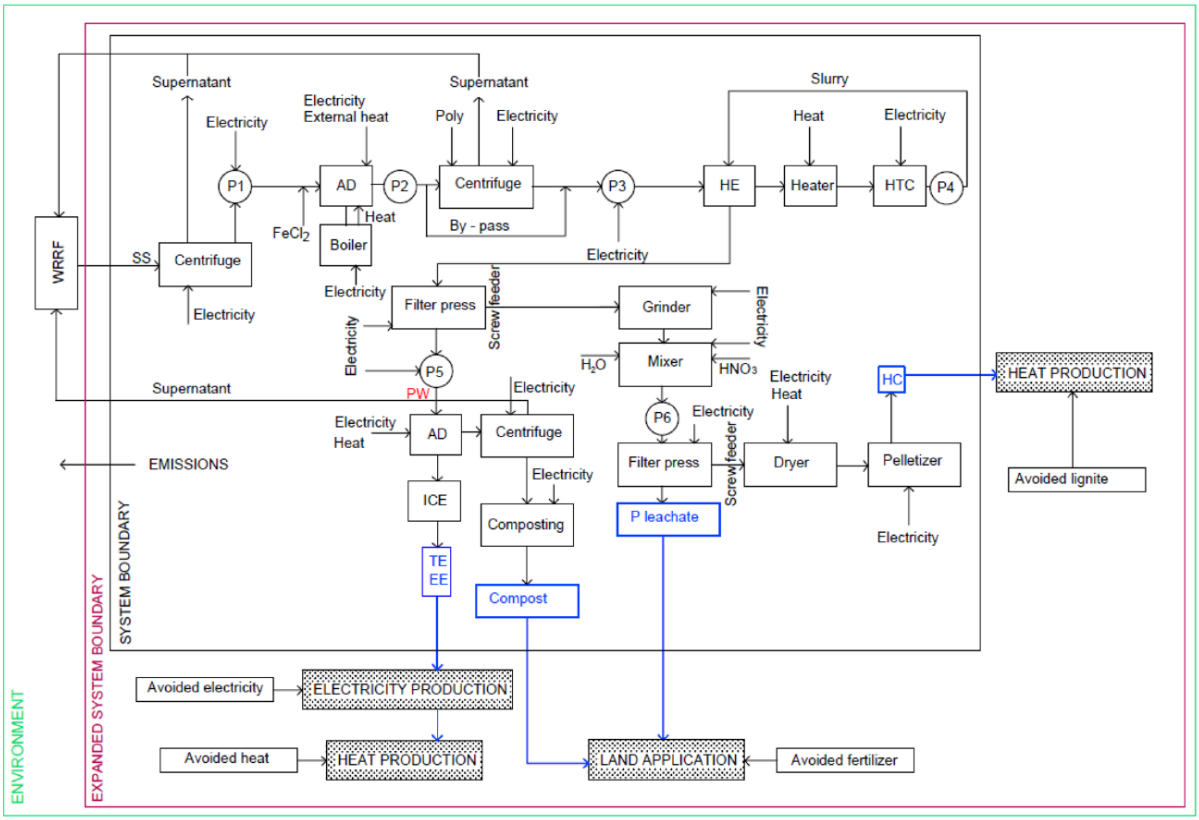


Figure 10: Hydrochar – Scheme of the HTC+AD+Pwet scenario, visualising the material and energy flows of an integrated hydrothermal carbonisation system for sewage sludge treatment, including process water valorisation via anaerobic digestion and phosphorus recovery (adapted from Mannarino et al. 2022).

Across HTC studies generally, the core **material transformation** is consistent: wet biomass feedstock enters the reactor and is converted, typically within 1–12 hours of retention time at mild temperatures (150–450°C) under autogenic pressure, into three fractions – a solid carbon-rich hydrochar, a liquid process water fraction rich in organics and volatile fatty acids, and a small gas fraction (mainly CO_2). From there, flows diverge depending on the scenario being studied: hydrochar may be dried and used as a solid fuel commonly substituting coal or lignite (Mendecka et al. 2020; Mannarino et al. 2022), applied to land as a soil conditioner, or further processed for nutrient (especially phosphorus) recovery via acid leaching. Process water is either treated conventionally (e.g., recirculated into a wastewater treatment line) or anaerobically digested to recover additional energy as biogas (Mannarino et al. 2022; Medina-Martos et al. 2020). Emissions tracked across these flows typically include direct process emissions (CO_2, CO from the HTC reactor and any auxiliary heating), fugitive methane from digestion or flaring, and combustion-related emissions (NOx, particulate matter, VOCs) from any boilers, engines, or flares used to recover energy from biogas or hydrochar. A widely used methodological convention is to treat CO_2 released from biomass-derived combustion as biogenic and therefore climate-neutral, while fossil-fuel substitution credits are calculated based on the stoichiometric CO_2 content of the displaced fuel.

Main Drivers: Several factors recur as the dominant drivers of environmental performance across the HTC LCA literature, independent of the specific feedstock or case study (Mannarino et al. 2022; Medina-Martos et al. 2020; Mendecka et al. 2020):

- **Fossil fuel substitution** is consistently identified as the single largest source of avoided impact when hydrochar is used for energy recovery – replacing coal or lignite tends to outweigh the direct process emissions of HTC itself, often by a wide margin, particularly for climate-related indicators.
- **Energy demand of the HTC process and any pre-treatment/upstream line,** needed for example to heat and maintain the HTC reactor at temperature, plus any pre-treatment and post-processing steps like dewatering and pelletising, is the main source of direct emissions in the process. This is partly mitigated by the fact that HTC, unlike pyrolysis, doesn't require pre-drying of wet feedstock, which would otherwise add further energy burden.

- **Valorisation of the liquid process water fraction** (typically via anaerobic digestion to produce biogas) is generally found to be environmentally beneficial, since it reduces the burden of having to otherwise treat a nutrient- and organic-rich wastewater stream, although the magnitude of this benefit is usually smaller than that of hydrochar's fuel substitution.
- **Nutrient (especially phosphorus) recovery steps**, when included, are frequently found to *worsen* rather than improve environmental performance – this is attributed primarily to the chemical inputs (commonly acids) required for extraction, which tend to outweigh the benefit of displacing conventional mineral fertiliser production. Multiple independent studies converge on this finding, suggesting it is a structural challenge of current P-recovery methods rather than a one-off result.
- **The choice of feedstock, processing technology, and valorisation pathway chosen for the solid product** is repeatedly flagged in the literature as the most influential factor determining whether HTC outperforms alternative treatment technologies. Bora et al. (2020), for instance, compared six different thermochemical conversion technologies – including HTC, pyrolysis, gasification, and hydrothermal liquefaction – applied to poultry litter, finding that the relative environmental and economic performance of each pathway depended heavily on which products (energy versus nutrients) were prioritised for recovery.
- **Dual use of the generated residual heat.** Biochar's LCA is also influenced if the residual heat generated during the process can be utilised and/or additional electricity can be generated. With HTC, the process steps can be separated and one part can be carried out in a decentralised manner and another part centrally, so that the requirements for electricity and heat generation and use can be optimised.

2.2.3 Co-benefits

Alongside timber construction with its substitution effects, biochar and to some extent also hydrochar have additional co-benefits. These were examined in detail in a literature review from September 2021 (H.-P. Schmidt et al. 2021). The co-benefits are very important, as they on the one hand reduce costs by allowing the added value to be sold, and on the other hand bring additional positive effects that make the use attractive, increase acceptance and can be assessed positively compared to the risks (e.g., PAH). Some co-benefits have positive effects on the absorption or reduction of GHG emissions, so they are also climate positive. A detailed report on Swiss soils prepared by the Federal Council shows that they have lost a massive amount of organic material, i.e., carbon, over the last few centuries through agricultural use, in some cases up to 78% (Swiss Federal Council 2023b). Biochar could therefore be a means of regenerating soils and storing carbon at the same time; another option is to build up humus. Both options can also be combined. The following co-benefits of biochar generally (Haubold-Rosar et al. 2016; Lin et al. 2023; H.-P. Schmidt et al. 2021) and of the HTC method specifically (Mehli et al. 2021) are mentioned in the literature:

Directly climate-relevant co-benefits of biogenic char

- Potential reduction of nitrous oxide (N_2O) emissions from the soil (Borchard et al. 2019)
- Binding of additional microbes and other biomass in the soil so that more C is stored
- Reduction of transport volumes through decentralised pressing and concentration of wet waste, such as liquid manure or sewage sludge, resulting in fuel savings (HTC)
- Reduction of methane emissions
    - from manure and sewage treatment plants,
    - through feed admixtures during the digestion of ruminants,
    - from soils (proven only for wet cultivation, e.g., rice).

Further co-benefits

- Improved feed intake in animals,
- Improved plant growth and increased yield in agriculture, especially if biochar was previously enriched, e.g. with manure or urine; the effect depends on the soil type
- Increase in soil pH if it is too low
- Storage of water in soils (however, large quantities of biochar must be added)
- Valuable subsoil in the cultivation of urban plants, through storage of nutrients and water, which leads to improved tree growth when used in the root zone
- Binding of bad odours, e.g., in wastewater treatment
- Binding of toxic substances (heavy metals) such as lead, chromium, or copper
- Improving the mechanical, thermal and electromagnetic properties of concrete
- Recovery of valuable resources such as phosphorus and nitrogen (HTC)

- Storage of energy that can be used again later through combustion (HTC)
- Degradation of harmful plastic residues in the biomass that would otherwise remain in the compost or fermentation residues, for example.
- Adsorption and immobilization of organic contaminants (PFAS)
- Elimination of PFAS during the pyrolysis process, in contrast to biomass composting that does not remove PFAS.

2.2.4 Risks

When applying biochar to soils, it is important to avoid the risk of harmful effects on soil physical, chemical, and biological properties. There is a lack of long-term studies (at least for European soils) to prove that the use of biochar does not pose a risk to humans and the environment; a scientifically sound upper limit has not yet been set (reaching the saturation level). FOEN has published a fact sheet on this topic (Federal Office for the Environment FOEN and Federal Office for Agriculture FOAG 2026). The most important risks are summarised below based on Haubold-Rosar et al. (2016) and Xiang et al. (2021). The European Biochar Certificate (EBC) was developed (starting 2012) to limit the risks of biochar usages to the best of scientific knowledge and to help users and producers of biochar to prevent or at least to reduce any hazard for the health and for the environment while producing and using biochar.[8]

Pollutant discharges

It is important to avoid negative effects from pollutant discharges and increased substance release in order to protect water, air and the health of plants, animals and humans. A targeted improvement in the environmental compatibility of the use of biochar in soils can be achieved by using low-pollutant and homogeneous starting materials during production. In all production processes, there is a risk of organic pollutant formation such as PAHs and dioxins during pyrolysis as well as highly volatile compounds, especially during hydrothermal carbonisation. The formation and uncontrolled release of these pollutants can be avoided through constant, controlled process management. Biochar that is certified using the EBC guidelines can be considered safe. For new feedstock or plants it is necessary to use and further develop appropriate technologies and, above all, to carry out independent controls of the chemical biomass decomposition process, which usually only industrial plants can afford (Haubold-Rosar et al. 2016). The Swiss Administration has recently published a fact-sheet with more information on the risks management (FOEN & FOAG 2026).

Soil pH, nutrient imbalances and ecotoxicity

Pyrolysis charcoals usually have pH values well above 7. Applied raw and fresh, this can lead to a high pH shock for plants because of release of readily soluble alkaline salts. If biochar is left to settle, especially if mixed with compost, this effect is much reduced. A study by Jaufmann et al. (2025) showed slight short-term effects of loaded biochar but expects rather positive long term effects for crop yields. Excessive or improper application of unloaded biochar could impair soil fertility and nutrient availability, but studies in European soil are very limited so far (Haubold-Rosar et al. 2016). Biochar may have some ecotoxic effects on soil biology, but there are also too little studies on this.

Carbon emissions
The production of biochar requires energy in the form of heat (usually own waste heat) and electricity in addition to the mostly fossil-based material transport to and from the plant, which are expected to be electrified in the future. If this energy comes from fossil fuels, it can contribute to GHG emissions and exacerbate climate change. In addition, biochar utilisation, e.g. in the steel industry, could release the stored carbon back into the atmosphere.

Environmental degradation

Large-scale biochar production could theoretically lead to increased demand for biomass, which in the worst case would lead to deforestation or diversion of agricultural resources. Such activities can disrupt ecosystems, reduce biodiversity and have negative consequences for land use and food production.

To mitigate these risks, it is crucial to follow independently controlled procedures in biochar production, ensure the use of clean, sustainably sourced raw materials, conduct adequate soil testing, and apply

[8] https://www.european-biochar.org/en/

biochar in appropriate quantities. In addition, rigorous monitoring and further research is needed to understand the long-term effects of biochar use on soil health, water quality and ecosystem dynamics.

2.2.5 Accounting

National accounting of biochar

Results of biochar application in agriculture and forestry are to be accounted for in the GHG inventory category of the Agriculture, Forestry, and Land-use (AFOLU) sector for its main effect of enhancing soil carbon content. The overall value chain involving the growth and harvesting of biomass – or the sourcing of waste-biomass – followed by processing through pyrolysis for biochar production is somewhat more complex though. The 2019 IPCC GHG Inventory refinements include specifications for the accounting of biochar in the AFOLU sector in the form of a *Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments* (Intergovernmental Panel on Climate Change (IPCC) 2019, Volume 4, Appendix 4). This allows a more detailed calculation to track the accumulation of carbon in soils through the application of biochar but it is only applicable for mineral soils in grasslands and croplands. It defines biochar as a solid material generated by heating biomass to a temperature in excess of 375°C under conditions of controlled and limited oxidant concentrations to prevent combustion through either pyrolysis or gasification. Resulting increases in soil carbon from biochar are estimated separately from other organic amendments over a 100-year time frame because biochar is more persistent (therefore the stock change method cannot be used): The methodology uses totals of biochar generated and added to mineral soil in cropland and grassland (not application rates) and ignores interactions between biochar and soil types or land management. However, the method requires tracking the source of biomass feedstock and the temperature of the pyrolysis to arrive at the biochar carbon content.

Currently, the Swiss National Inventory for GHG emissions is not accounting for biochar removals, since no program is registered under FOEN guidelines. Biochar removals are only certified under voluntary carbon standards that have no effect on the national GHG inventory.

Looking forward, the IPCC Task Force on National Greenhouse Gas Inventories has been mandated to deliver a methodology report on CDR, CCS and CCU by the end of 2027, which is expected to provide additional guidance on how removals – including from biochar – should be reported in national GHG inventories under the UNFCCC (Edwards et al. 2026).

Project-based MRV of biochar projects

Biochar has the largest market share of all removal project types in the voluntary carbon markets, with about 3 Mt of biochar credits having been contracted between 2022 and the first half of 2025, and with deliveries and retirement roughly doubling annually, signalling a strong growth trend (CDR.fyi 2025). With average market prices of 132 US$ and 136 US$ in 2024 and 2025, respectively (Johnstone et al. 2026), biochar projects remain the cheapest among the novel CDR approaches, which explains their attractiveness among buyers.

There are a number of programs and standards that offer CDR products on the voluntary carbon market. One of the first programs was offered by First Climate based on the ISO 14-064-2 standard that sold the first 124 tCO_2 removed by biochar in 2019. The voluntary carbon standard Verra released a methodology for biochar utilisation in soil and a non-soil application in August 2022. Since then, this methodology has been updated (Verra's VM0044, version 1.2, June 2025). At the same time there are new institutions that develop carbon standards which only focus on CDR, including Puro.earth with its first biochar methodology in May 2019 or CarbonFuture with its C-Sink certification standard related to the European Biochar Certification (EBC).[9] As shown in Table 3, which compares some of the most known voluntary market standards with the Swiss and the European ones, these different standards have very similar requirements on biochar quality (i.e., following the EBC quality control) but differ in their determination of the baseline scenario, project emissions (e.g., how they include emissions for sourcing of biomass), leakage and system boundaries, additionality and the quantification of the long-term stable removal effect of biochar (permanence).

More importantly, the EU Carbon Removal Certification Framework has moved from rule-setting to implementation: the first delegated regulation, adopted in February 2026, establishes a certification methodology for biochar carbon removal (Delegated Regulation 2026/285). The certification landscape

[9] https://www.european-biochar.org/en/

for biochar removals is thus converging. A recent comparative assessment of the three most consequential frameworks – the EU CRCF, the Integrity Council for the Voluntary Carbon Market (ICVCM) Core Carbon Principles and the Article 6.4 mechanism – finds that they increasingly share requirements on biochar quality, permanence and monitoring, but still differ in their treatment of baselines, additionality and, crucially, how removals relate to national GHG inventories and corresponding adjustments (Thoppil et al. 2026). For Switzerland, the central point is unchanged: biochar removals certified only under voluntary standards do not enter the national inventory, and it is the alignment of these frameworks with inventory and Article 6 accounting that will determine whether Swiss biochar removals can eventually be counted toward national climate targets.

Table 3: Overview of main carbon removal standards applicable to biochar (Own work based on the discussion at the DeCIRRA online workshop on 20.03.23, updated as of June 2026).

Standards / Criteria	**Puro.earth**	**Verra Carbon Standard** (voluntary, USA)	**European Biochar Certificate** (voluntary, Europe)	**Swiss CO_2 Ordinance**	**European Union** Carbon Removals and Carbon Farming (CRCF)
Allowed use		According to method VM0044: crops, grasslands, products such as biochar-amended concrete and building materials		Fertiliser / soil application (up to 1 t/hectare/year); as construction material	Defined by Del. Reg. 2026/285: biochar covered as a permanent removal ("BCR") activity
Allowed raw materials	Sustainable biomass, waste biomass, and biomass grown explicitly for biochar	Specified in the method VM0044	See EBC positive list	Specified in Fertilizer Ordinance; incl. plant biomass processed only physically, biowaste from separate collection. Animal byproducts excluded unless treated. Sewage sludge excluded.	Defined in the methodology (sustainable biomass feedstock criteria, consistent with EU sustainability rules
Additionality	To be proven individually, e.g., investment analysis	Additional as long as less than 5% of the waste biomass globally is used for pyrolysis (not for energy generation)	No proof required	Expected to be investment analysis	Standardised zero-baseline approach: any activity generating net carbon removal is deemed additional; other sources of finance (e.g. subsidies) allowed with no implication for additionality.
Permanence (duration of storage and leakage risk)	100 years	100 years	100 years	30 years	1000 years (random reflectance method), or 200 (decay function method)
Accounting / MRV	According to Puro method	According to method VM0044	According to sequestration method EBC C	According to own method to be developed in a FOEN project	Lifecycle accounting across the full biochar production and application chain, including uncertainty assessment and conservative default factors
Transparency (governance, register)	Puro register	Verra register	Carbon Standards International register	FOEN register	EU certification via Commission-recognised certification schemes, audited by accredited bodies;

					units recorded in an EU registry (under development)
Prevention of double use / double counting (corresponding adjustments)	Voluntary market: no double counting as long as biochar is not considered in national emissions inventories	Voluntary market: no double counting as long as biochar is not considered in national emissions inventories	Voluntary market: no double counting as long as biochar is not considered in national emissions inventories	As soon as projects are possible, it will be considered in the inventory	Addressed through CRCF QU.A.L.ITY criteria and the EU registry; registry allows interoperability between certifiers to prevent double claiming; interaction with national inventories/Article 6 to be managed as the registry and ETS-linkage rules develop; use of units toward third-party NDCs or CORSIA prohibited
Inclusion in national inventory	Not foreseen in the standard	Not foreseen in the standard	Not foreseen in the standard	Yes, prerequisite is the entry in the land register	CRCF is a voluntary EU certification framework, not itself an inventory mechanism; certified removals may in future inform compliance instruments (e.g., possible EU ETS integration)
Baseline	No project (BAU)	No project (BAU)	No project (BAU)	Not yet clear; depending on the programme; probably no project (BAU)	No project (BAU); to be updated every 4 years
Sources	Puro.earth	Verra 2025a	EBC	CO_2 Ordinance	Thoppil et al. 2026; Implementing Reg. 2025/2358; Del. Reg. 2026/285

2.2.6 Estimates of costs, potentials, and main drivers

Costs

Biochar is one of the few CDR technologies where co-benefits can generate income to partly offset the cost of CO_2 sequestration. These must therefore also be taken into account for the comparison with other technologies. A distinction must therefore be made between the production costs for biochar (both investment and running costs) and the revenue side, which consists of the sale of biochar and the by-products (heat, electricity, gas). The final costs of biochar depend on the possibility of monetising these. A distinction is made between two variants: In variant 1, biochar cannot be sold, but is only used to store CO_2 in designated storage sites. In variant 2, all co-benefits can be sold and biochar serves as a valuable product, e.g., in agriculture or construction. Depending on the variant, the resulting net costs (difference between costs and revenues) per tCO_2 of the negative emissions generated by biochar vary greatly and depend on the specific use.

In addition, the costs differ greatly depending on the form of production:

- Industrial, energy-led production process, with additional revenues from energy sales
- Industrial, material-led production process
- Agricultural self-consumption.

Finally, there are other by-products and considerations for HTC plants than for pyrolysis plants. The long list of co-benefits shows how complex it is to predict the true costs and potential revenues. Since HTC may recover phosphorus, for example, this process alone can be lucrative if the phosphorus price is right.

Most of the larger Swiss production plants are currently at a very early stage of production, i.e. most of the plants are not yet running optimally and full time. For example, the plants have to be repeatedly shut down in order to optimise processes.

There are various data on costs in the literature, but these are very widely dispersed and therefore only of limited usefulness (A). Current selling-prices for biochar can be found on the internet (B), most of this char is produced in small plants that have not yet been industrially optimised.

***A) Costs for the production** of one tonne of biochar (2-3 tonne of CO_2e):*

According to Cames et al. (2023), international studies have indicated costs of 8-300 US$/t$CO_2$ for the production and use of biochar. In Switzerland, the estimates for the year 2030 are CHF 30/tCO_2 and CHF 10/tCO_2 for the year 2050. Other studies have estimated the costs at 10-135 CHF/tCO_2, depending on the pyrolysis process, the origin of the biomass and the quality of the biochar. This results in a large uncertainty about the costs. In addition to production, the total costs also depend on the costs of storage. These vary depending on whether biochar is injected into the ground or used in construction. The new FOEN factsheet assumes current production costs at 300–750 CHF per tonne of biochar based on the Prognos and Infras Study (Prognos & Infras 2021).

***B) Revenues from the sale** of biochar (in niche markets in small quantities)*

In Switzerland, sale prices for biochar range from around 500 CHF (untreated, unspecified biochar) to 2,500 CHF (microbially activated feed charcoal) per tonne, depending on the intended use and quality. Table 4 displays current market prices for biochar found through internet research on sales portals:

Table 4: Sales prices of biochar in the Swiss market.

Product	Sales details for 1000 l	Price per tonne biochar
Activated biochar in compost soil	70% biochar for 699 CHF	3,300 CHF / tonne
Pure biochar, not activated	100% biochar for 370 CHF	1,200 CHF/ tonne
Biochar for animal feed	Ground biochar for 740 CHF	2,400 CHF / tonne

**Assumption: density of around 0.3 kg / l*
Sources: https://www.swiss-biochar.com/produkte/, https://agrarshop.ch/Verora-Futterkohle-gemahlen-Big-Bag-1.0m3/AGS1028792

These revenues do not reflect the production costs or the prices for the NET technology, but are rather determined by downstream processes that are related to the co-benefits, such as the use as feed additive, and can vary greatly. It can be assumed that revenues, i.e., the market price of biochar, will decrease significantly as soon as production is scaled up industrially.

Negative emission potentials of solid char

The potential of biochar and hydrochar as carbon removal pathways in Switzerland is ultimately bounded by a single, finite resource: the amount of biomass that can be sustainably harvested or retrieved from waste without competing with other uses. How that resource gets allocated, between energy production, carbon removal, and traditional material use, is not fixed, and can shift depending on climate targets and market conditions. On top of that physical constraint sits a second, independent one: even where biomass is available and converted into char, the resulting product still needs a buyer. Market absorption capacity, meaning how much char private buyers (or the state) are actually willing and able to purchase or subsidize, can cap real-world deployment well below what is technically producible. This section lays out both constraints in turn: how much biomass exists and how it might be allocated, then how much of the resulting carbon removal potential the market can currently absorb. To discuss these questions for Switzerland and find solutions, an expert group was formed out of the DeCIRRA project, comprising industry and research partners, that will continue on these topics within the Carbon Removal Platform: Taskforce for Bio-based Solid Carbon Removal (TF BSCR).[10]

Availability of biomass based on current estimates

Thees et al. (2017) estimate Switzerland's sustainably available biomass potential, beyond what is already in use, at 2.8 Mt of dry matter per year (44.2 PJ). A FOEN publication (Jakob 2022) arrives at a broadly consistent figure: if all sustainably available dry biomass were converted to biochar and incorporated into soil nationwide, the resulting sink potential would be around 2.2 Mt CO_2/year. Estimates vary across studies mainly because they start from different assumptions, particularly around

[10] https://www.carbon-removal.ch/en/working-groups

which biomass type is used (for example waste streams versus purpose-grown biomass), so the exact ceiling on large-scale biochar production and use remains an open question. The current allocation is not fixed: it may shift over time as the balance between carbon removal and energy production evolves, and biomass production itself could be scaled up if required to meet climate targets. In our SES-ETH model, this allocation is therefore treated as a variable that moves toward whichever technology and energy configuration is optimal. Based on the model results, the TF BSCR postulates that the amount of available biomass can be greatly increased by reallocation from energy use and optimal biomass production.

The market-side constraint
While the pyrolysis production process for biochar has already reached commercial maturity (TRL 9), plant capacity and biomass supply currently limit how much can actually be produced. The CDR Report of the Risk Dialogue Foundation (Beuttler et al. 2019, pp. 41–42) estimates a maximum market volume of 600,000 tonnes of biochar per year, corresponding to 2.2 Mt CO_2e sequestered, even though up to 900,000 tonnes per year could technically be produced, more than the market is currently estimated to absorb. This market-volume estimate assumes application is cost-free or even cost-negative for biochar once co-benefits are factored in; accounting for these co-benefits (including the substitution of light heating oil), this volume of biochar could offset around 18% of Swiss emissions. A more recent estimate from Brunner and Knutti (2022) puts the direct sequestration potential of biochar at a more conservative 1.5 Mt CO_2e.

Reallocating priorities: carbon removal over energy use
Most existing estimates assume biomass for energy use is prioritised, with carbon removal treated as secondary. DeCIRRA's net-zero modelling with the SES-ETH model challenges that assumption: it shows that energy needs could instead be met by other renewable sources, freeing up biomass to be prioritised for carbon removal instead. Building on these modelling results and current literature, Figure 11 shows a quite different removal potential.

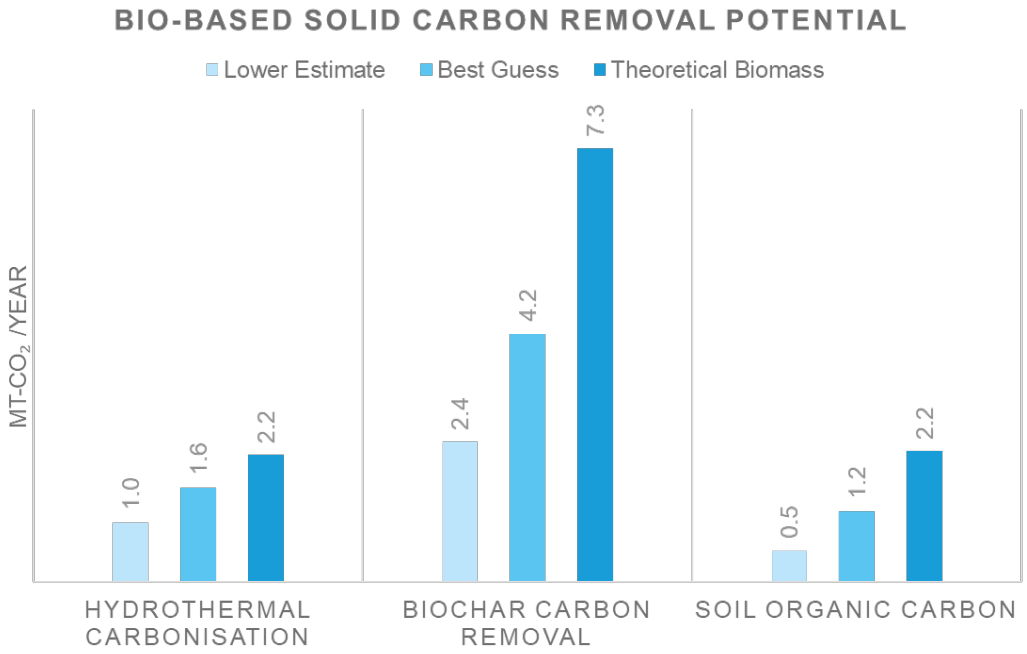


Figure 11: Potential bio-based solid carbon removal estimates for hydrochar, biochar and soil organic carbon pathways in 2050 (Biomass data (Burg et al. 2018), CDR stabilisation factors (Keel et al. 2025; Schmidt et al. 2021)).

The DeCIRRA BSCR expert group suggests a biomass carbon removal strategy to redirect biomass residues to carbon removal under the following priorities. The following biomass allocation is suggested:

- Dry, carbon-rich biomass: pyrolysis for biochar production
- Wet, contaminated biomass: hydrothermal carbonization for hydrochar with geological storage
- Nutrient-rich, clean biomass: stabilised for soil carbon enhancement and nutrient recycling

In order to optimise the climate benefit of biomass toward net-zero, the following steps need to be taken by land owners: 1. ***Reduce*** emissions from biomass production; 2. Increase biomass productivity (***Restore***); 3. Stabilise biomass for carbon ***Removal***. Following these priorities, the BSCR pathway could deliver around 7 Mt CO_2 in removals by 2050, alongside reduced agricultural emissions and better adapted agro-ecosystems. Because redirecting biomass from waste toward carbon removal creates a stronger financial incentive to produce more eligible biomass, the total potential could grow beyond current inventories, and more ambitious agricultural net-zero targets could shift the sector from a net emissions source to a net sink.

The competition for wood in practice
A key obstacle to scaling biochar production is the limited future availability of source material, especially wood. Dry biomass is already in high demand as an energy source, a demand set to grow further as the heating sector decarbonises and biomass increasingly substitutes for coal, oil, and gas. Forest residues and wood chips, in particular, are contested: they are needed both for the heating market and as a biochar source for agricultural use. Roundwood destined for timber construction should not be used for carbon removal at all, which is also shown by our Energy-Model: TCCS is the preferred option in all scenarios. This timber should only be used in CMA once deconstructed for cascading biomass use. Nevertheless, it can be expected to still remain in high demand as a raw material precisely because it is dry, compact and easy to transport and store.

The competition is expected to intensify, particularly for woody biomass, which makes up roughly a third of the total available resource. By 2030, most woody biomass is expected to be committed to the heating market under long-term contracts, sharply limiting what remains available for pyrolysis. As our implementation partner Thomas Fedrizzi puts it: "*As things stand today, biochar is a new sales segment for the forestry industry because not all residual forest wood goes into the energy cycle. This will be different in 2030. On the other hand, biochar costs too much for widespread agricultural use due to the complex process for it to be bought in bulk or for forest wood chips to be paid as much for pyrolysis as for energy chips. The competition between heat production and CO2 storage will remain fierce.*"

Storage

Biochar is not yet used as a NET to any significant extent in Switzerland. The main use of biochar is currently in agriculture as a soil conditioner and less as a material additive in construction or other applications.

The use of biochar in agriculture is currently strongly regulated in Switzerland by the FOEN. Chapter 2 of the new factsheet describes this process, which is fairly involved: it requires certification of the production plant as well as regulatory approval of the biochar as a fertiliser, including regular quality testing (FOEN & FOAG 2026).

The geological storage of char (biochar and hydrochar) as a CO_2 sink is currently not in focus in Switzerland (Cames et al. 2023). HTC is assigned by the authorities to a residual category of "technology-open" options for which no specific regulatory or financial framework yet exists (Swiss Federal Council 2021). The Climate and Innovation Act (KIG), in force since January 2025, creates financial support instruments for novel CDR technologies, and HTC-based storage could in principle qualify (Hafner et al. 2025). However, this potential is not yet operationalised.

The central regulatory obstacle is the legal regulation of waste. In a written statement from February 2025, FOEN classified hydrochar as waste under the Waste Ordinance (ADWO), applying pyrolysis waste codes without distinguishing between pyrolysis and HTC. Two specific provisions block storage: Article 30c, Ziff.1 of the Environmental Protection Act (EPA) requires that landfilled materials contain as little organic carbon as possible and Annex 5 of the ADWO sets a total organic carbon (TOC) limit of 5% by weight for type-E landfills, as high TOC substances could be used as energy source in Swiss incineration plants. This directly contradicts CDR-motivated HTC, where a high TOC is necessary to store as much carbon as possible. According to a mail exchange with FOEN, a regulatory revision is currently not planned. However, Article 48a of the EPA provides since 1.1.2025 a potential pathway for innovative pilot projects, allowing the Federal Council to introduce temporary, geographically and materially limited exemptions in order to gather experience for the further development of environmental legislation and its implementation.

The use of char in other applications such as animal husbandry, environmental technology, energy technology and as a material, is still being researched and currently only accounts for a very small proportion of utilisation.

Overall, there is substantial research and innovation regarding the use of biogenic char in construction, for example as an additive in concrete (Singhal 2023), but also as a base material for insulation, e.g. from the startup Kohlenkraft.[11] The potential for this utilisation is difficult to estimate, as most projects are still in the pilot phase. According to the "Biochar-zero" association of biochar experts, such building materials can also be certified with the European Biochar Certificate (EBC). In this case, the biochar only needs to correspond to the lowest quality class, so such utilisation could be very interesting in order to use various source materials for biochar production.[12]

Main drivers for costs and potentials

Currently, the main drivers of the costs and potential of biochar are as follows:

- Improvement and professionalisation of plant manufacturers, consolidation of the market so that it is less confusing.
- Uncertain development of the biomass market and the cost of biomass. This is influenced by the demand for biomass from other sectors and also, for example, by the weather or pest infestations that may result in a sudden and unforeseen large amount of wood waste.
- Authorisation and acceptance of alternative resources as feedstock, such as liquid manure or food waste or faecal sludge from wastewater treatment plants.
- Acceptance in agriculture depends above all on the price and the authorisation procedures as well as the certification procedures, e.g., organic. In addition, of course, on the tangible positive characteristics, which may reduce other costs (irrigation, fertilisation, etc.).
- Constant testing of the quality of biochar and clear certification of certain qualities for certain uses.
- Reimbursement of CO_2 storage through certificates.
- Support of biochar in agriculture by the Swiss administration, through the definition of clear utilisation recommendations (quantities and quality) and user groups.
- Simplification of processes – e.g., omitting registration in the land register and instead introducing a simple registry.
- Association of producers and users in organisations, such as Charnet, which promote use and make the possibilities better known.
- Introduction of and information about biochar in the relevant training programmes so that its use becomes better known.
- Biochar is cheaper, simpler, less dangerous and more efficient for storing carbon, as CO_2 does not have to be produced first, which then has to be stored again. Carbon is stored here without detours and without the reaction with oxygen, so that the end-product has around 1/3 less weight and much less volume (as a solid compared to a gas) and can therefore be stored and transported more easily.
- Mitigation through biochar will be greatest where biochar is applied to responsive soils (acidic, low fertility), where soil N_2O emissions are high (intensive horticulture, irrigated crops), and where the syngas co-product displaces fossil fuels (Nabuurs et al. 2023).

Downstream, i.e., when biochar is actually in demand and produced, the following additional drivers emerge:

- The fixed costs depend primarily on the size and professionalism of the plants, i.e., significant economies of scale are to be expected.
- The operational costs depend on the initial substance (cost and quality), and then of course also on the economies of scale. Slurry, for example, is cheaper, but must first be dewatered. However, there are already technical solutions for this and, with mass production, significant cost reductions can also be expected here.
- Revenues depend on the extent to which the benefits are perceived or real savings are achieved through the use of biochar, e.g. animal health. Depending on this, the willingness to pay could even be higher in the construction sector than in agriculture. This also depends on the regulations for CO_2 avoidance in the construction sector.

[11] https://kohlenkraft.ch/
[12] https://biochar-zero.com/construction-industry/biochar-in-concrete/

2.2.7 The role of hydrochar/biochar across scenarios

Our modelling results show that biochar is part of the optimal CMA mix in all four scenarios, with the highest share in the Snail scenario where CO_2 transport costs are high and the lowest share in the butterfly scenario. In the snail and clam scenarios hydrochar is also part of the optimal CMA mix. Unlike biochar – where operators receive a payment for the biochar itself – hydrochar storage must be paid for. As a result, hydrochar capacity is only built out in scenarios that already feature higher marginal CO_2 removal costs (i.e., the clam and snail scenarios). In these two scenarios, hydrochar reaches with 1 Mt CO_2/year a significant deployment level and becomes an important component of the domestic carbon removal portfolio. See Figure 12.

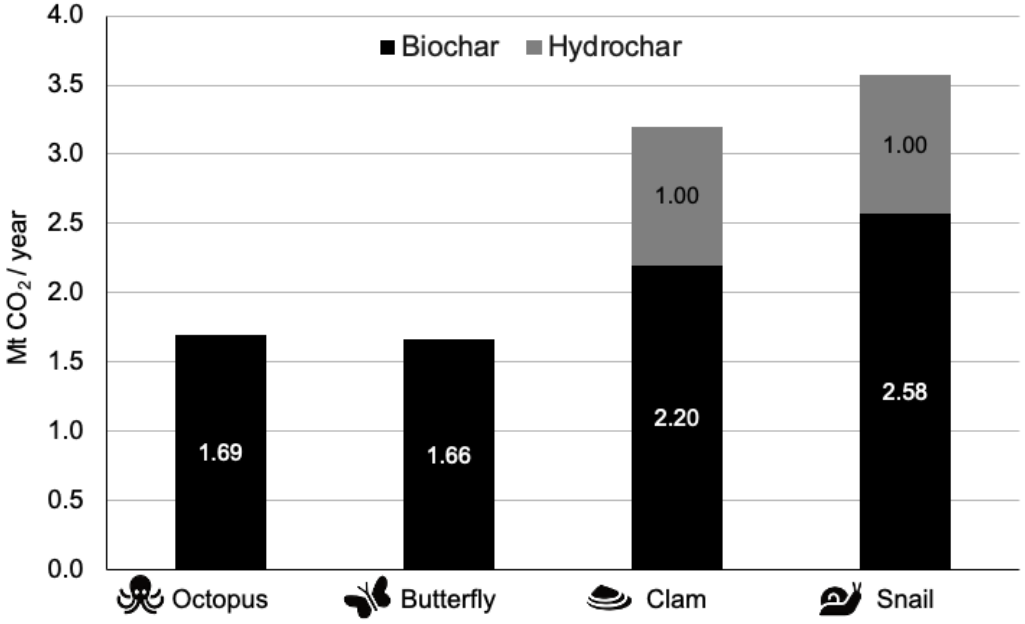


Figure 12: Use of biochar and hydrochar within Switzerland in the DeCIRRA scenarios (Mt CO_2/year).

2.2.8 Relevant actors

Many different players are active in the biomass sector in Switzerland. The following actors are particularly important; other more general actors are mentioned in Section 3.1 and can be found in our list of actors.

Federal Office for the Environment (FOEN) and FOAG (Federal Office for Agriculture): They play a crucial role in regulating and monitoring the production and use of biochar and publish factsheets (FOEN & FOAG 2026). In addition, the FOEN supports research and development initiatives related to biochar and other climate protection technologies. There are currently no major biochar storage sites in Switzerland. Abroad, only geological storage sites can be recognised as CO_2 sinks under the compensation instrument of the CO_2 Act, as there are no established measurement and control mechanisms. Nevertheless, the Swiss government supports biochar projects abroad, for example as part of the REPIC project, which aims to promote renewable energies, energy efficiency and resource efficiency in developing and transition countries (Cames et al. 2023).

Research is being conducted at several institutions, including Agroscope, Fibl, WSL, HES-SO and HEPIA Geneva. In addition, Lignocarbon, IWB, Verora, AgroCO2ncept and Ökozentrum are working on the development and testing of industrial pyrolysis technologies for plant carbonisation. Lignocarbon has already gained a great deal of experience. Agroscope in particular is conducting studies on the effects of biochar on soil quality, plant productivity and climate protection. Agroscope also provides recommendations and guidelines for farmers and policy makers on the use of biochar.

The Swiss Federal Institute of Technology (ETH Zurich), ZHAW, Ökozentrum Langenbruck and other universities are actively researching biochar and its potential for carbon sequestration, soil improvement and sustainable agriculture, and some are operating pilot plants.

Wastewater treatment plants (WWTPs): Sewage sludge is an important raw material for HTC technology. At the same time, the technology is a way for sewage treatment plants to utilise their waste products more efficiently.

Swiss Climate Foundation: The Swiss Climate Foundation supports projects to reduce GHG emissions and promote sustainable technologies. It has funded research projects focussing on biochar and its role in carbon sequestration and climate protection.

Organisations and associations: Swiss Biochar Research Network (SBRN) and Charnet: The SBRN is a network of researchers, practitioners and stakeholders dedicated to promoting biochar research and application in Switzerland. They work together on projects, exchange knowledge and promote sustainable biochar practices. Charnet Switzerland raises awareness, offers training and further education, and promotes cooperation between interest groups, including farmers, researchers, and political decision-makers. In this context, European organisations such as the European Biochar Industry Consortium and the Ithaka Institute, their certificates (European Biochar Certificate (EBC)) and the EU legislation are also very important for Switzerland, as Swiss regulators are usually guided by them.

Farmers' association and farmers: The implementation of soil management measures and the main use of biochar is carried out by farmers; in other areas, such as urban horticulture, city gardeners are responsible.

Recoal and GRegio are among the emerging **Swiss industry actors** developing projects based on hydrothermal carbonisation (HTC). GRegio develops, plans and constructs HTC plants for the treatment of wet biomass, including sewage sludge. Recoal develops Biomass Carbon Removal and Storage (BiCRS) projects that convert wet residual biomass into stable hydrochar and permanent underground storage. Together, these activities cover important parts of the value chain from HTC technology and plant implementation to the development of verified carbon removal projects.

The industrial production of biochar is also being strongly promoted by **Swiss energy suppliers**, some of which operate biomass power plants in addition to hydroelectric and solar power plants and therefore have experience in this area. An example is IWB[13] in Basel, Energie360° or Inkoh AG.

Organisations and companies that **operate marketplaces** or develop and **finance NET** projects are important for implementing projects and ensuring the flow of funds, for example myClimate and South Pole. This also requires close co-operation with the financial industry. These connections are not yet so well developed in the biochar sector, as mostly small local projects have been implemented in Switzerland to date.

Construction industry and start-ups that promote the use of biochar in the construction industry, e.g., in cement or as an insulating material. KLARK[14] from the company LOGBAU, for example, is the first concrete in Switzerland to contain biochar and thus store CO_2. Kohlenkraft[15] has pilot projects in the areas of insulation and plaster.

Public
Public perception about biogenic char is especially important, when char is not being used in agriculture, but stored underground. According to our survey (see Section 2.6.4), the public prefers solid storage compared to CO_2 (gaseous) storage, which could be important to drive projects forward for storage sites within Switzerland.

2.2.9 National and international policies and incentives

In Switzerland

[13] https://www.iwb.ch/klimadreh/ratgeber/co2-einsparen/pflanzenkohle
[14] https://www.klark.swiss/
[15] https://kohlenkraft.ch/

The Swiss government allows the use of biochar for compensating emissions in the transport sector, through its application in agriculture and the construction sector.

For use in the construction sector, a sustainable production of the biochar has to be ensured (CO_2 Ordinance, Appendix 3).

The rules on the use of biochar as fertiliser in the agricultural sector as a compensation project have been updated. Such use is permitted if the biochar meets the requirements of the Fertilizer Ordinance of November 1, 2023, and complies with the maximum annual application rate specified therein (CO_2 Ordinance, Appendix 3). In addition, it has to be demonstrated that the sequestered CO_2 remains in the soil for at least 30 years (CO_2 Ordinance, Article 5.2), and the land area used as a biological carbon sink must be noted in the land register upon application (Article 8a).

More generally, the Swiss legal framework for the use of biochar in agriculture under the Fertilizer Ordinance was updated in 2024 so that it is now more aligned with the EU Fertilising Products Regulation (EU 2019/1009). Biochar is classified under Component Material Category 14 (CMC 14, pyrolysis/gasification materials). This broadens the permitted feedstocks from virgin wood to nearly all plant biomass, including separately collected bio-waste (sewage sludge and untreated animal by-products, including manure, remain excluded), provided the resulting biochar has a molar ratio of hydrogen to organic carbon below 0.7. Switzerland is stricter than the EU in three respects: process additives are capped at 10% of feedstock fresh mass (vs. 25% in the EU); pyrolysis conditions are more demanding, likely to ensure decontamination; and heavy metal, PAHs, and polychlorinated biphenyls (PCB) limits apply to biochar itself (not just to blended end products). This matches the European Biochar Certificate EBC-AgroBio certification class and its stricter Swiss PAH threshold (4 vs. 6 mg/kg). Producers may register biochar via Switzerland's Product Register for Chemicals, which is cheaper than EU REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals, according to regulation EC No. 1907/2006 governing chemical substances) registration, and must obtain approval from the Federal Office for Agriculture, with EBC certification (Swiss annex) accepted as sufficient proof of compliance (Hagemann 2025).

A recently updated fact sheet published by FOEN and FOAG (2026) shows that the Swiss government does in principle support biochar projects, however, it has a cautious approach to biochar application, especially regarding potential risks for soils and the environment. For this reason, the marketing of a fertiliser consisting in whole or in part of biochar is subject to authorisation under the Fertilizer Ordinance. In addition, the Chemical Risk Reduction Ordinance (ChemRRV, Annex 2.6, Section 3.2.4) specifies a maximum application rate for biochar of 1 tonne/hectare per year, with a maximum of 10 tonnes per hectare allowed over a period of 20 years (FOEN & FOAG 2026).

These rather strict requirements currently in place limit the viability of biochar projects under the Swiss compensation scheme. In addition, the application of biochar to soils is not economically viable for farmers, even after accounting for the carbon removal certificates, as biochar currently costs too much. Only if all benefits of biochar (i.e., reduced nitrogen losses, improved animal husbandry and soil fertility) and its production process (e.g., heat and electricity from the pyrolysis process) are accounted for, the application by farmers in soil may become attractive.

Biochar projects are at present therefore more attractive for the voluntary market – which does not allow the Swiss government to account those removals in its inventory.

Finally, there seem to be several trade-offs with regard to sustainable sourcing of biomass for biochar production and also the accounting of the above-mentioned co-benefits. Higher quality wood needs to be used in a cascade first as construction material and only later pyrolysed. Incentives need to be set by regulation in a way that this cascading is happening and that the co-benefits are all accounted for, thus that biomass ends up in the place where it will provide the highest social benefit for Switzerland and not where the willingness to pay is the highest or subsidies provide distortions (e.g., due to renewable energy support for wood incineration plants).

With regard to using hydrochar for solid carbon storage underground, an important legal limitation arises because stored hydrochar (unlike biochar) is currently classified under the Waste Ordinance as an industrial or waste-derived byproduct, i.e. as a type of waste, while at the same time its chemical properties prevent its disposal in underground structures: The organic carbon content of hydrochar (both in the solid fraction and the leachate) is specified for waste landfilling according to the Waste Ordinance. More specifically, as explained above, EPA Article 30c, para. 1 requires that landfilled materials contain

as little organic carbon as possible and Annex 5 of the ADWO sets a total organic carbon limit of 5% by weight for type-E landfills.

Internationally

A recent review of the literature on policy support for biochar application (Pourhashem et al. 2019) concludes that, at least in the US, there currently aren't any policy incentives that would allow monetization of the positive external effects (on water quality, soil carbon sequestration, among others) of its application. However, the article illustrates how biochar can fall into broader categories of products (such as biobased products or value-added agricultural products) that may be eligible for policy support under existing schemes. Considering these definitions, the authors found 35 policies that directly or indirectly support biochar in the US, including financial incentives, non-financial policy support and funding for research and development. Among these, for example, they identified a loan guarantee scheme for biorefineries and biobased product manufacturers, which provides guarantees for up to 80% of the total eligible project cost, and that has already been applied to an industrial-scale biofuel and biochar production plant. Among the non-financial support measures are policies that explicitly consider biochar as a technological option to address specific environmental needs, such as forest conservation or climate change mitigation. Despite these existing schemes, the authors point out that biochar has so far been less successful than other bioproducts such as biofuels in receiving the available support.

Pourhashem et al. (2019) also identify the lack of product certification or standards as a major challenge for this technology, because this lack makes its environmental benefits and properties less well-defined. The authors describe improvements in this area, led by the International Biochar Initiative, which has established an international biochar quality standard. Within the US, however, certification is so far voluntary and not uniform.

On the voluntary carbon market, biochar remains by far the most widely traded durable carbon-removal method: according to CDR.fyi, biochar carbon removal has accounted for the large majority of all durable CDR credits actually delivered and retired since 2022 (around 86–92% of deliveries and retirements), even though bioenergy with carbon capture and storage (BECCS) dominates the volume of forward contracts (CDR.fyi 2025). This reflects biochar's comparatively short project lead times and low capital intensity. At the same time, questions of durability, quality and consistent accounting have driven a rapid consolidation of certification standards.

The accounting framework for biochar removals is advancing substantially on two tracks. First, under the Paris Agreement, the Article 6.4 Supervisory Body adopted at its October 2024 meeting the "Standard: Requirements for activities involving removals under the Article 6.4 mechanism" together with a standard on the development and assessment of methodologies, and these were endorsed on the opening day of COP29 (CMA6) in Baku in November 2024 (UNFCCC 2024a; UNFCCC 2024b). This removed a key procedural barrier to operationalizing what is now branded the Paris Agreement Crediting Mechanism (PACM), as this framework establishes general rules for permanence, monitoring, and reversal risks. A dedicated biochar methodological tool is still under preparation (Thoppil et al. 2026), but as of mid-2026 no such methodology had been submitted for approval, and the Article 6.4 list of approved methodological tools does not include a biochar methodology. Once such a methodology is adopted, it would in principle allow Parties – potentially including Switzerland – to use biochar removals for compliance purposes and to record them against their Nationally Determined Contributions, subject to the corresponding adjustment rules of Article 6.

Second, in the European Union the Carbon Removal and Carbon Farming (CRCF), Regulation (EU) 2024/3012, is now in force and being implemented. In February 2026 the Commission adopted the first delegated regulation establishing certification methodologies for the three permanent-removal activities considered sufficiently mature: direct air carbon capture and storage (DACCS), bioenergy carbon capture and storage (BioCCS) and biochar carbon removal (BCR) (European Commission 2026a; Delegated Regulation 2026/285). The CRCF Regulation is a voluntary EU-wide standard: it defines what counts as a tonne of removal, how permanence must be ensured, and how risks such as reversals and liability are addressed, and is complemented by an implementing regulation on certification schemes, bodies and audits (Implementing Regulation 2025/2358). Although Switzerland is not bound by the CRCF Regulation, the framework is likely to become a de facto quality benchmark for removal credits traded in Europe and may shape the standards that Swiss projects and buyers align with.

In parallel, integrity initiatives in the voluntary market have matured. The ICVCM has begun assessing durable-removal programs against its Core Carbon Principles; in December 2025 it confirmed the removal-focused registry Puro.earth, whose methodologies cover biochar, as a Core Carbon Principles

(CCP)-eligible carbon-crediting program, although the biochar methodology itself remained pending separate CCP-methodology approval at that point (ICVCM 2025). Taken together, the finalization of the Article 6.4 removals standards (with a biochar-specific methodology still in preparation), the EU CRCF Regulation, and stricter voluntary-market integrity standards mark a clear shift for biochar from a purely voluntary-market commodity toward frameworks that could eventually allow removals to be counted in national inventories – the key limitation identified for the Swiss context in the section above.

2.2.10 Business models

Biochar exhibits the greatest business model diversity and the highest current commercial maturity compared to other CMA. Out of 30 analysed companies in Europe only the 15 biochar ones have viable business models and are in growth phase (Lagler 2025). Companies combine pyrolysis equipment sales, direct biochar product revenues (from soil amendment, construction applications, and technical substrates), CO_2 certificate sales, and waste heat and electricity revenues. This multi-stream revenue architecture allows cost recovery without subsidies under favourable conditions (Lagler 2025), though recent Swiss data indicate this is more challenging in the agricultural context than previously estimated (FOEN & FOAG 2026).

Gaido (2026) shows in his thesis that stakeholders interviewed describe a technology at TRL 8–9 that is already commercially deployed in Switzerland. The dominant barriers lie not in the technology itself, but in restrictive application regulations imposed by the FOEN, among them the 1 t/ha/year application limit and the looming removal of feed-grade biochar from the organic-farming list, as well as in a market structure in which CDR revenues cover only a fraction of production costs. This profile deviates from the classic Valley-of-Death logic, which typically describes a gap between technological and commercial maturity. In the case of biochar, the TRL dimension has already been overcome. The "valley" instead lies between demonstrated commercial deployment readiness and regulatory and market-side recognition as a CDR service at the CRL and SRL level. Classical R&D funding does not structurally address this core problem; what is missing is a regulatory opening combined with demand-side market development.

Hydrochar shows a related but not identical profile. At TRL 7, the technology is operationally proven. According to Gaido (2026), a first pilot plant is currently being delivered. The dominant barriers here, too, lie at the CRL and SRL level: high investment costs and the absence of standardised quality criteria are hampering market entry (Guidati et al. 2024). Biochar and hydrochar therefore share the basic pattern of a shifted Valley of Death, but differ in their CRL maturity: biochar already generates commercial revenue, whereas hydrochar is on the verge of entering this phase.

Another solid **biomass** CDR approach based on **algae** represents an important exception within the portfolio examined. The stakeholder interviewed describes a technology in transition from laboratory to pilot scale (TRL 5–6), where technological maturity remains a relevant bottleneck. Unlike biochar, BECCS, and DACCS, the primary bottleneck here is not the CRL/SRL dimension, but the technology itself, which must first be further developed and proven. This exception demonstrates that the pattern of "TRL outpacing CRL and SRL" is not a universal rule, but depends on the development stage of the respective technology.

The algae-based approach also holds potential relevance for one of the central resource challenges facing biomass-dependent CDR technologies more broadly: competition for scarce biomass. Since algae can in principle be cultivated on non-agricultural land using sunlight and, where available, nutrient-rich waste streams, self-produced algae biomass could – if production costs, energy demand, and nutrient inputs can be kept sufficiently low – represent a partial solution to the competition for limited organic residues that constrains biochar and BECCS scaling in Switzerland. Two possible business models exist: replacing fossil fuels with algae-based carbon, or using the algae itself as feedstock for biochar or hydrochar production. Evidence suggests that production at scale must be located in either very sunny or low-energy-cost regions, meaning Swiss companies may be best positioned in the role of technology developer and operator rather than large-scale producer. Whether this potential can be realised remains contingent on resolving the current technological gaps, but it makes the algae pathway strategically interesting beyond its carbon removal potential alone.

2.2.11 Main conclusions and future research

Timing: The production of biochar via pyrolysis and hydrochar via HTC are technologies that can convert various forms of biomass into solid carbon, thereby contributing to negative emissions. First industrial-scale plants are already in operation, therefore they are a carbon management approach which can already be invested in.

Potential: Both processes compete for the scarce resource of biomass – pyrolysis for dry biomass and HTC for wet biomass (e.g. pyrolysis vs. wood chip heating; HTC vs. sewage sludge incineration). HTC has the advantage of being able to utilise a range of wet biomass feedstocks, including manure and sewage sludge, and allows cascading use – for example, following biogas production. The process also enables the recovery and reuse of phosphorus and nitrogen.

Costs: Sequestration as hydrochar or biochar is comparatively cost-effective as a negative emissions technology (NET), with costs already achievable below CHF 150/tCO_2e. However, biochar projects only become viable when biochar is sold and additional revenue is achieved. According to FOEN and FOAG (2026), biochar use in agriculture is, in most cases, not currently economically viable, and that even with a long-term decline in price to around CHF 500 per tonne of biochar, field application does not pay off as long as certificate sales remain the only revenue stream and willingness to pay for stored CO_2 does not rise substantially.

Quality: The quality of the resulting solid carbon products varies by process and feedstock, particularly with regard to stability and composition. Quality requirements exist for biochar; for hydrochar this is still missing. Potentially contaminated materials such as old/waste wood, municipal waste, or sewage sludge are prohibited as biochar feedstocks under Swiss fertiliser law (FOEN & FOAG 2026). Both products have distinct application profiles and should be used or stored close to the point of production – biochar, for example, in agriculture or as a soil amendment. Both products can be used in construction as admixtures in concrete. Further storage options include former mining sites, but regulatory barriers prevent those to be used.

Standards/methodology: Since January 2024, biochar has been explicitly regulated as its own material category (Component Material Category 14) under the Swiss Fertilizer Ordinance. Bringing biochar to (the agricultural) market now requires authorisation, the responsible federal office can mandate regular quality testing, and the biochar content must be disclosed on accompanying documentation (FOEN & FOAG 2026). This represents meaningful national progress on standardisation but leaves unresolved the international gap: no biochar methodology yet exists under Article 6.

Accounting: Cross-border accounting of biochar soil applications under the Paris Agreement is unresolved, since biomass and biochar transfers across national borders are still not consistently tracked, making accurate crediting of removals difficult. There exists a “Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development”, by the IPCC (2019).

Regulation: Eliminating existing legal contradictions and barriers is necessary for scaling solid carbon products, as well as creating enabling frameworks that allow for production, storage, certification and trading – and in particular pilot projects –, and alignment with the EU and with countries that have more experience in this area. Current Swiss legislation prevents or impedes sequestration both in shallow and deep subsurface storage. Regulatory sandboxes would be beneficial for promoting the sequestration of solid carbon (BiCRS approach) in Switzerland.

Durability/Permanence: The question of carbon storage permanence also shows movement, though it remains fundamentally difficult due to the simple fact that long-term experiments that last a few hundred years are practically impossible. A long-term Swiss field study ("Black goes Green"), running since 2021, is now generating real field data on biochar’s effects on soil biology over time, but is not published yet. However, the FOEN factsheet itself confirms that long-term field data under typical Swiss agricultural conditions are still lacking, and current decay-rate estimates (likely below 0.3% per year) remain provisional rather than confirmed (FOEN & FOAG 2026). However, Swiss soils do not distinctively differ from other soils in temperate climates, speaking for an international (European) approach to perform further research on the permanence estimate of biochar, depending on feedstock, pyrolysis conditions and biochar physical-chemical data.

Co-benefits: There is still no emerging EU certification framework that systematically addresses biodiversity and broader ecosystem effects alongside carbon accounting; this remains a stated ambition without methodological detail. The challenge of monetising co-benefits – such as soil fertility or water quality improvements – alongside the core climate benefit remains unaddressed; the new Swiss factsheet (FOEN & FOAG 2026) provides cost figures for biochar production but does not attempt to assign monetary values to these secondary ecosystem services.

Risks: A five-year field trial with still unpublished results found that earthworm biomass declined by 28–30% two to three years after applying high biochar doses (8 t/ha) to agricultural soil, although populations appeared to recover after four years (FOEN & FOAG 2026). But this study is not yet published, the applied amounts seem to be higher than normal, and it remains unclear how the biochar was treated before deployment, e.g. “loaded or not”.

2.3 Timber Carbon Capture & Storage (TCCS) – Engineered Wood

2.3.1 General description

The real estate sector causes more than 24 Mt CO_2e emissions per year, with approximately 30% of them attributable to upstream supply chains, including the production of construction materials (Frischknecht et al. 2020). Against this background, wood as a renewable bio-based material is increasingly considered a promising lever to decarbonise the built environment's grey emissions while enabling long-term storage of biogenic carbon in buildings over their service life.
Photosynthesis binds atmospheric CO_2 into biomass, and the carbon is stored in the wood. On average, one tonne of CO_2 equivalent is stored in one cubic metre of wood (see Figure 13).

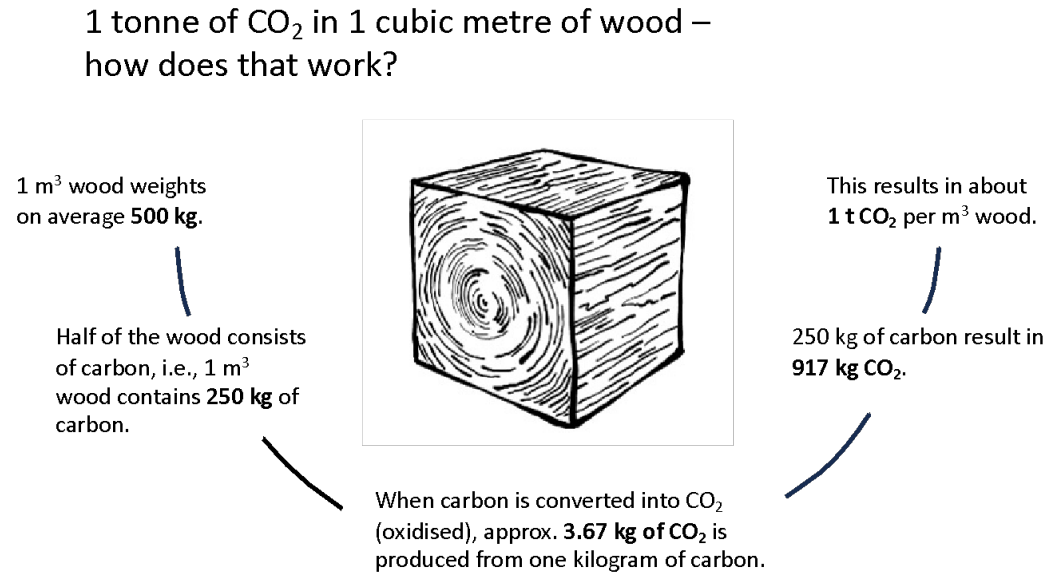


*Figure 13: Conv*ersion of the biogenic carbon stored in one cubic metre of wood into carbon dioxide (CLB Schweiz GmbH).

When wood is used in buildings, the biogenic carbon previously sequestered in forests can remain stored in construction products for decades to centuries, depending on the building's service life and the end-of-life management of the material. If circular or cascade-use strategies are implemented, timber components may be reused following demolition or recycled into subsequent applications, thereby prolonging the storage duration. Upon combustion, however, the biogenic carbon contained in the timber is oxidized and converted back into atmospheric carbon dioxide. Where bioenergy with carbon capture and storage (BECCS) is applied or biochar is produced, a share of these emissions may be captured and permanently stored, resulting in negative emissions. Moreover, substituting conventional construction materials such as steel and concrete with timber can reduce the embodied GHG emissions of the built environment.

Sustainable forest management is the precondition for any wood flow that can credibly be counted as a climate contribution. Climate change, however, is already altering growing conditions and therefore the Swiss *Integrale Wald- und Holzstrategie 2050* (Swiss Federal Council 2025b) calls for climate-adapted, diverse and resilient mixed stands. The wood-processing industry needs to become capable of handling those new species and different assortments.

Today, in timber construction, mainly coniferous (softwoods) are used and, thanks to new technologies, increasingly also hardwoods such as beech. The CO_2 storage capacity of hardwood (e.g. beech) is around 1.2 t CO_2 per cubic metre compared to softwoods with a CO_2 storage capacity of around 750 kg CO_2, which is why more attention should be paid to hardwood from this point of view in the future.[16] The

[16] Calculation provided by Timbercarbon: 1 m³ of beech wood weighs roughly 680–720 kg, of which about 50 % of the dry mass is carbon; with a stoichiometric factor of 3.67 kg CO_2 per kg C, one cubic metre stores the equivalent of some 1.2–1.3 tCO_2. Worked example: 700 kg m³ × 0.5 = 350 kg C; 350 × 3.67 ≈ 1,285 kg, i.e. ≈ 1.29 tCO_2 per m³ of beech wood. However, not all hardwoods are denser or heavier than softwoods. Bulk density (mass per unit

heat energy required to dry fresh sawnwood to the lower moisture contents of construction timber is largely obtained from wood processing by-products, which is why it is considered CO_2-neutral. Electricity for the mechanical processes and the fans in the drying kilns can be accounted for on the basis of the Swiss consumer electricity mix, while the large roofs of wood mills are increasingly fitted with solar cells, so that the direct CO_2 emissions for electricity are zero. Transport emissions depend on the selected transport routes and vehicles (lorries, goods trains).

Since the revision of the Fire Protection Ordinance in 2015, timber construction has been possible in Switzerland for every building category, including apartment blocks and high-rise buildings (Bader 2022). In contrast to alternative construction methods, timber construction is less resource- and emissions-intensive. On the other hand, it allows the carbon sequestered from the atmosphere in the forest to be stored in buildings for up to 200 years assuming that the service-life of the construction is maximised and options of reuse or cascading are realised. (Bader 2022).

Timber Carbon Capture and Storage (TCCS), also known as "Timber in Construction" (UNFCCC 2022), is the term used to describe the use of wood (preferably mass timber) in the load-bearing structural elements of multi-storey buildings, which are therefore installed for around 100 years until the planned end of the building's life. The long-lasting use of timber building materials enables long-term Carbon storage in the Swiss building stock. As around four times more building materials are used in Switzerland than are dismantled and as long as more wood is used than is disposed of, this results in net Carbon storage (Savi and Klingler 2022).

Around 800,000 m^3 of wood were used in construction in Switzerland in 2020 (in walls, ceilings, façades, roof trusses, but excluding insulation materials, stairs, indirect material and furniture) (Winterberg et al. 2022). Construction timber used in Switzerland is fully traceable and does not come from primary forests. It is generally sourced from managed forests within regulated and often certified supply chains, both in Switzerland and abroad.

In 2025, 211,450 m^3 of sawn timber were processed in Swiss mills into glued laminated timber for construction, which corresponds to a decrease of 1% compared to the previous year (Holzindustrie Schweiz 2025). It is assumed that around 75% of construction timber is imported (FOEN 2022), although verification of the country of origin is complex and is therefore usually unknown despite the requirements in the Timber Trade Ordinance. A large proportion of construction timber in Switzerland comes from Germany, Austria and Eastern Europe.

2.3.2 System boundaries, material and emissions flows, and main drivers

The most important elements and system boundaries for accounting the climate impact and other environmental burdens of timber building materials are the supply of biomass, the manufacturing of wooden construction materials, their use in buildings and their end-of-life processing. The carbon flow of the forest and wood products subsystems can be found in Figure 14.

For the climate impacts of the forestry sector, it is the total biogenic carbon stock that is relevant as well as the total amount of carbon emitted to the atmosphere. For this, the system can be divided into `forest' and 'wood products' subsystems (see Figure 14). The total biogenic stock is the sum of the C-stocks in the subsystems. The yellow boxes show processes within the economy that are subject to change. This includes the carbon intensity of substitute materials, which is expected to change over time as energy systems evolve, production technologies advance, and carbon capture and storage (CCS) is potentially implemented, in addition to the emissions associated with wood processing.

The definition of system boundaries for forest-wood-based CMAs is a matter of ongoing debate, above all with respect to the treatment of carbon which was stored in harvested trees (see Box 2 below).

volume) varies considerably between tree species. The specific CO_2 uptake capacities or CO_2 equivalents given here therefore apply to spruce (750 kg) and beech (1.2 t). Poplar and willow, as lighter hardwoods, are closer to spruce than to beech.

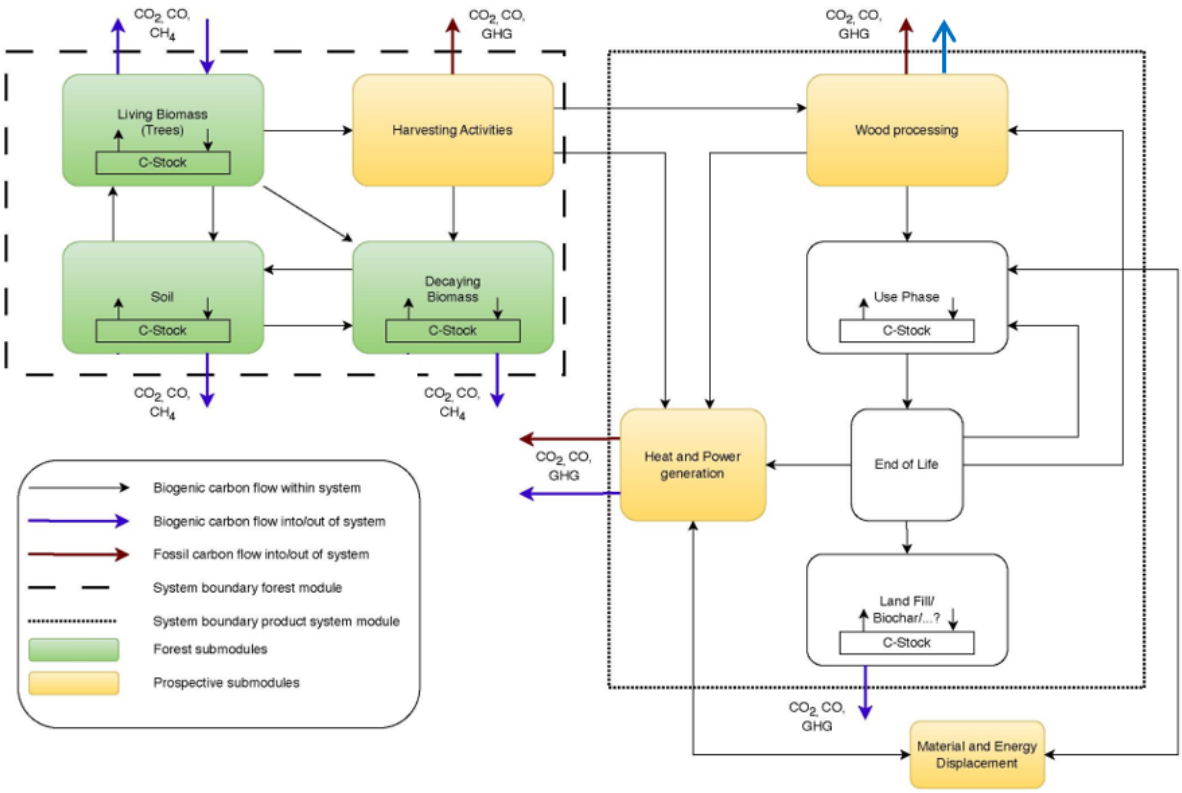


Figure 14: TCCS whole life cycle, visualizing key issues in the carbon accounting.
Note: Landfilling of waste wood is banned or effectively phased out in most of Western and Central Europe

BOX 2: System boundaries and reference scenarios in forest–wood accounting
Whether wood construction appears as a climate solution or a climate liability depends less on the underlying data than on how the forest is brought into the accounting. Much of the apparent controversy in the literature is therefore methodological rather than empirical: differing system boundaries, reference scenarios and time horizons produce widely diverging results from broadly comparable inventories. Maierhofer et al. (2024, p. 624) illustrate this: “The research results indicate that under current production conditions the common view of wood as a climate change mitigation option shifts, as the achieved GHG substitution effects of wood construction are overshadowed by the unrealised carbon storage potential in forests. Our research highlights the large carbon sink effect of forests, which exceeds the GHG substitution effects achieved by the use of wood in our case study scenarios. In developing LCA methodologies for wood-based materials, it is essential to consider these effects on the carbon storage potential of forests. Given the current net-zero GHG targets, forests and their carbon sink potential, which is bound to come under pressure, must be preserved and enhanced. Recognising this fact is vital to achieve climate neutrality on planet Earth.”

Two asymmetries in that boundary setting deserve attention. First, on the product side the study assumes release of the stored carbon at the building's end of life through combustion without BECCS or comparable capture, and without cascading or reuse; the authors themselves note – qualitatively – that accounting for reuse would shift the results, which argues for modelling it quantitatively rather than as a caveat. Second, on the forest side no end-of-life scenario is modelled at all, although every individual tree has one: mortality, disturbance, windthrow, drought or bark beetle attack release CO_2 and, under waterlogged or anaerobic decay, methane. This risk is real but not deterministically calculable, and it is rising precisely because of climate change. Accounting needs to address those emissions as well.

The two omissions do not cancel out: the first systematically understates the long-term potential contribution to removing carbon dioxide permanently, the second systematically overstates the permanence of the forest sink. Meaningful comparison requires symmetric treatment: full life-cycle boundaries on both pools, including realistic end-of-life pathways for wood products (cascading, reuse, capture) and explicit mortality risk for the trees including extreme weather events, which are predicted to increase with climate change. This will increase complexity but will be closer to reality.

The origin of wood is important, because environmental burdens can be substantial if it does not originate from sustainable forestry. Potential changes in biomass stocks in forests and forest soils as a consequence of harvesting trees need to be taken into account. If trees from dedicated plantations are harvested, direct and indirect land use changes and associated climate impacts and other environmental burdens must be considered. If wood from sustainable origin must be considered as a constrained resource in a certain geographic area, the consequences of its use as construction material instead of other purposes, for example energy generation, need to be taken into account. In Switzerland and in the European Union, wood is highly traceable along the value chain and covered by regulations to avoid any risk of deforestation also covering imported wood (i.e. the EU Deforestation Regulation).

Using wood as load bearing supporting structure construction material allows for (temporary) storage of biogenic carbon. How wooden construction materials are reused or disposed of at end-of-life determines when and whether their stored Carbon is released into the atmosphere (e.g., through waste incineration) or permanently removed through geological storage (if the incineration plant has CCS). Another option for removing and storing the carbon after end-of-life is to convert the material into biochar. Since the end-of-life of buildings built today or in the future is unknown, it is recommended to include several different scenarios (reuse, incineration with and without CCS or storage in biochar) in the accounting and to quantify the effect of those. The same holds true for the lifetime of buildings (Cordier et al. 2022).

Regarding the temperature effect, the duration of Carbon storage in wooden construction materials is critical: if the carbon is released after this period, the associated CO_2 emissions and climate impacts are effectively delayed rather than avoided. As a result, the temperature reduction achieved by using wood as temporary carbon storage (relative to not storing it at all) diminishes as the CO_2 is re-emitted, as illustrated schematically in Figure 15 (Ciais et al. 2014, p. 548). To properly assess the climate impacts of timber as construction material, the use of harvested wood products needs to be integrated with forest carbon balance analysis (Geng et al. 2017).

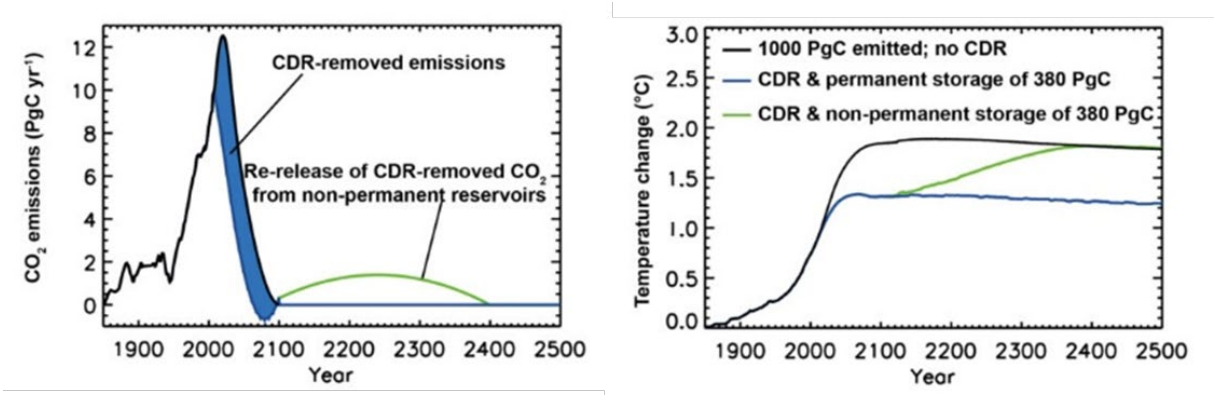


*Figure 15: Visualisation of (temporary) Carbon*storage and associated temperature effect on a global level for a certain amount of CO_2 (temporarily) stored (Ciais et al. 2014, p. 548).

If the system boundary is broader and the focus is not only on the stored carbon, substitution effects may be included in the LCA. Timber products may substitute conventional materials like concrete, bricks and steel, and effects of such substitution in terms of reduced or increased environmental burdens may also be quantified. In general, substituted products can be assumed to be avoided (in terms of their production), and environmental reduction equivalent to the burdens associated with their production, can be accounted for. Quantifying such substitution effects must be based on equivalent functionality of construction materials within the context of the built environment and must cover the entire lifetime of a building (taking into account potentially different lifetimes of components) including maintenance or needed refurbishments, if any (Gustavsson and Sathre 2011). Potential impacts on the operational energy demand for heating and/or cooling of buildings should be taken into account, in case these differ. It is essential to maintain a clear distinction between, and to report separately, atmospheric CO_2 removals and emission reductions attributable to substitution effects.

Life cycle of a timber building

Figure 16 and Figure 17 display in different ways the life cycle of a timber building and the life cycle stages relevant to its carbon footprint. Figure 16 shows all possible wood uses and end-of life options whereas Figure 17 focuses on construction waste as waste disposal.

Some numbers in both figures have been disputed by timber experts and the missing carbon reduction in forest was criticised: According to them, the cradle to gate relation of 0.66 is too high in Figure 16 and the 27% loss in storage during the use stage is too high in Figure 17.

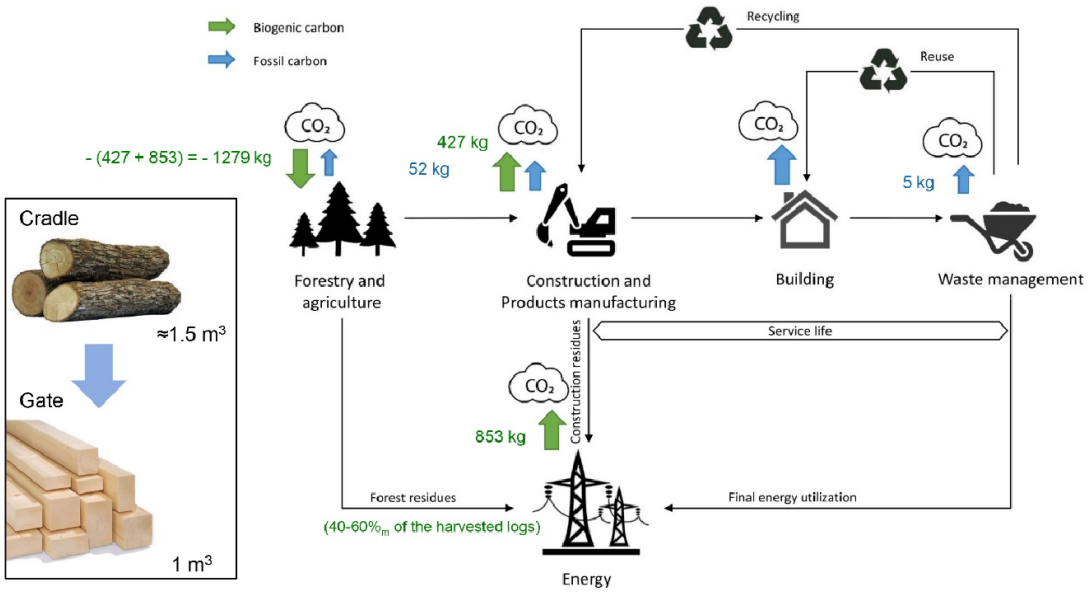


Figure 16: Simplified illustration of the life cycle of a timber construction and the carbon flows generated per life cycle stage (Pittau et al. 2022, p. 15).

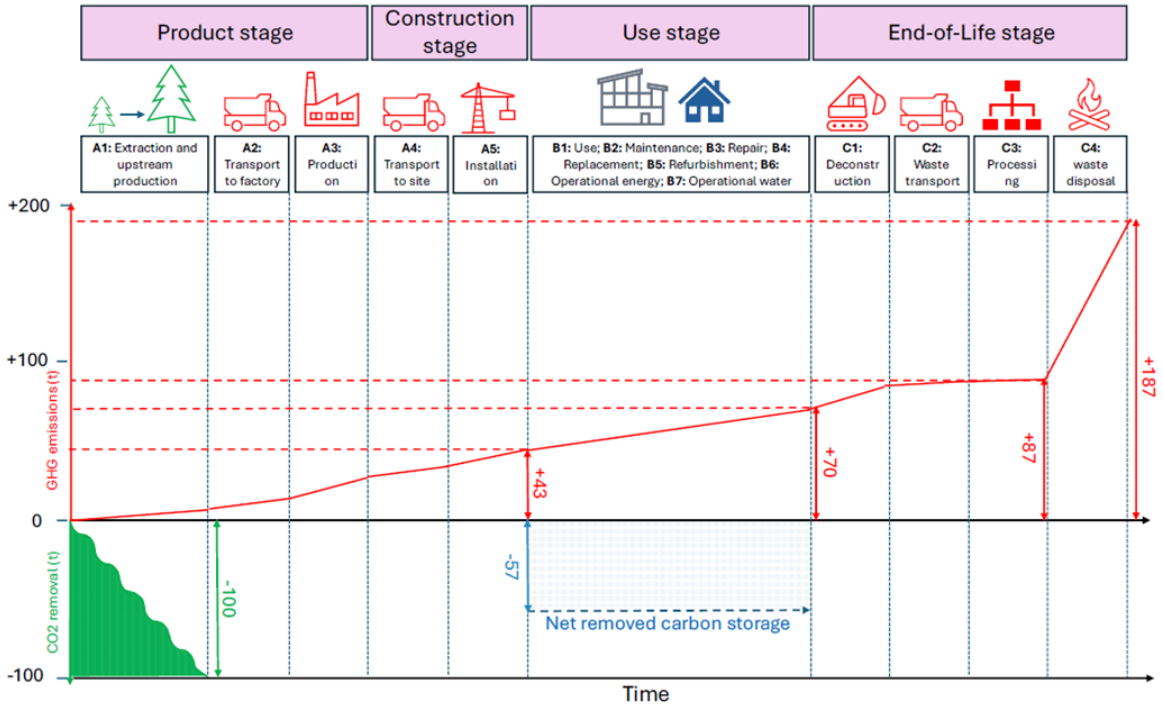


Figure 17: Schematic illustration of removals, emissions and storage of net removed carbon over the full building life cycle (arbitrary numbers but proportionate to each other) (DG CLIMA & Viegand Maagøe 2025).

Figure 18 compares the GHG emissions from the production, transport and disposal of 1 m³ of glued laminated timber (glulam) produced in Switzerland (example 1), Germany (example 2) and Hungary (example 3) and imported into Switzerland. The glulam produced in Hungary causes 79% more GHG emissions than the one produced in Switzerland. The electricity mix for machining and processing and

the transport emissionshave a strong influence on total emissions. In example 1, transport causes 16% of emissions, in example 3 it causes 35% (Frischknecht and Ramseier 2020).

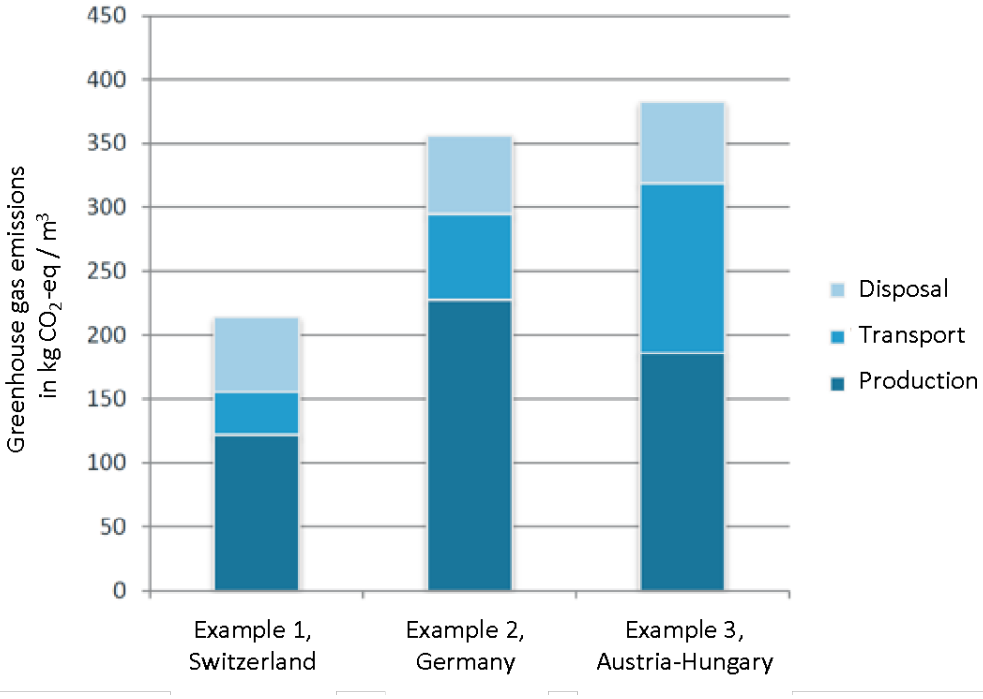


*Figure 18: Differences in the GHG emissions cau*sed for 1 m^3 of glued laminated timber produced in Switzerland, Germany and Hungary (Frischknecht and Ramseier 2020, p. 11).

Wood procurement
Timber harvesting is usually carried out using machines that run on fossil fuels. There are opportunities to reduce these emissions by replacing them with electrically powered machines, however this may take time.

The prerequisite for timber procurement in terms of TCCS is that the forests are not overexploited, as this leads to a reduction in CO_2 sequestration in the forest and biodiversity loss. Forest management systems such as FSC and PEFC help to ensure that imported timber comes from safe and controlled sources. In contrast to areas where tropical wood is used (decking, flooring), construction timber rarely comes from primary forests, so there is no link between Swiss timber construction and carbon flows in primary forests.

Production
Wood-based materials are manufactured using a mix of biogenic and fossil fuels. Wood is usually dried in the wood processing plants using wood residues from sawmilling (Pittau et al. 2022). The adhesives used in the production of structural timber are usually sourced from fossil fuels.

Transport
In Switzerland and Europe, round timber and construction timber is mainly transported by lorry. Timber imported from abroad is also mainly transported by lorry.

The use of low-emissions or electric vehicles can have a positive impact on the CO_2 balance. The transport of construction timber causes the largest proportion of manufacturing emissions when construction timber is imported (own calculation with the treeze wood calculator[17]). For Swiss timber, an average transport distance of approx. 190 km is assumed, which means that the emissions from transport are somewhat the same as the emissions from production.

If there were no imports, Switzerland's entire wood requirements would have to be met from regional wood. This could lead to overexploitation of forests and additional emissions and costs, as wood from inaccessible, remote regions would have to be transported by helicopter, for example. At the same time,

[17] https://treeze.ch/fileadmin/user_upload/calculators/631-Holzrechner_v1.0.xlsx

new technologies would have to be standardised that allow the constructive use of lower-quality wood (e.g., Scrimber).

Type of wood
The type of wood has an influence on the carbon content in the construction timber. Higher density hardwoods (e.g. beech, oak, ash) tends to be dried for longer than the lighter softwoods. However, as the drying process uses mainly residual wood energy, it can be considered low carbon and energy efficient.

End of life
When construction timber is burnt, it mainly emits biogenic carbon, which corresponds to the carbon content of the wood. If construction timber is reused or fed into the cascade, these emissions can be postponed, and the carbon storage time is extended. However, they only count as negative emissions in the long term if either BECCS or pyrolysis is used at the end of life.

2.3.3 Co-benefits

Timber construction can generate several co-benefits aligned with the Sustainable Development Goals.

First, timber is a renewable bio-based material that can support a more resource-efficient construction sector. Its use can contribute to waste reduction, especially through prefabrication, optimised material use, and the valorisation of by-products and residues. Compared with more mineral-based construction systems, timber construction may also reduce water consumption in certain production and construction processes. In addition, timber has potential for circularity through reuse, repair, design for disassembly, and cascading use, although these practices are still not fully developed at market scale. These aspects are particularly relevant to SDG12 - Responsible Consumption and Production.

Second, timber construction supports innovation and industrial development in the building sector. The increased use of engineered wood products, digital planning, prefabrication, and advanced timber engineering can contribute to modern, low-carbon construction practices and strengthen regional value chains. This aligns with SDG9 - Industry, Innovation and Infrastructure.

Third, when timber is sourced from sustainably managed forests, it can support responsible forest management and provide an economic incentive to maintain forests as productive, resilient landscapes. This contributes to SDG15 - Life on Land, provided that sourcing safeguards and sustainability criteria are met.

Directly climate-relevant co-benefits

Substitution of other building materials
In addition to the Carbon storage that timber construction offers, the most important co-benefit is the avoidance of CO_2 emissions through the substitution of other building materials. Figure 19 shows 10 case studies in which timber buildings are compared with their mineral and functionally equivalent twins in terms of grey GHG emissions. In all cases, the mineral buildings have higher grey GHG emissions during construction. The timber buildings have 12%-41% lower grey emissions at building level (see in column "Building" the difference between the values of the timber building compared to the mineral twin). The biogenic carbon listed in this column corresponds to the carbon removed from the atmosphere during tree growth, which is now stored in the building component, relative to the total GHG emissions. It is listed as a negative percentage of total emissions (Lamster 2023), but may not yet be included in a balance of grey GHG emissions. The report notes the following: "*The biogenic carbon content (...) cannot be included in a balance of grey greenhouse gas emissions. From a climate perspective, greenhouse gas emissions and biogenic carbon are two different effects that cannot be summarised in one figure. Grey greenhouse gas emissions are shown as the cumulative total of all emissions generated during production. The emissions are already emitted when the building is completed. The biogenic carbon is removed from the atmosphere during tree growth and is only emitted again during decomposition or energy utilisation. It is stored in the wood until the wood decomposes or is burnt. Biogenic carbon is therefore stored in the standing tree or in timber in use. However, when considering compensation measures in the short term over the next few years, it is conceivable that the biogenic carbon content in the form of emitted CO_2 emissions could at least be compared with the balanced greenhouse gas emissions*" (Lamster 2023, p. 18).

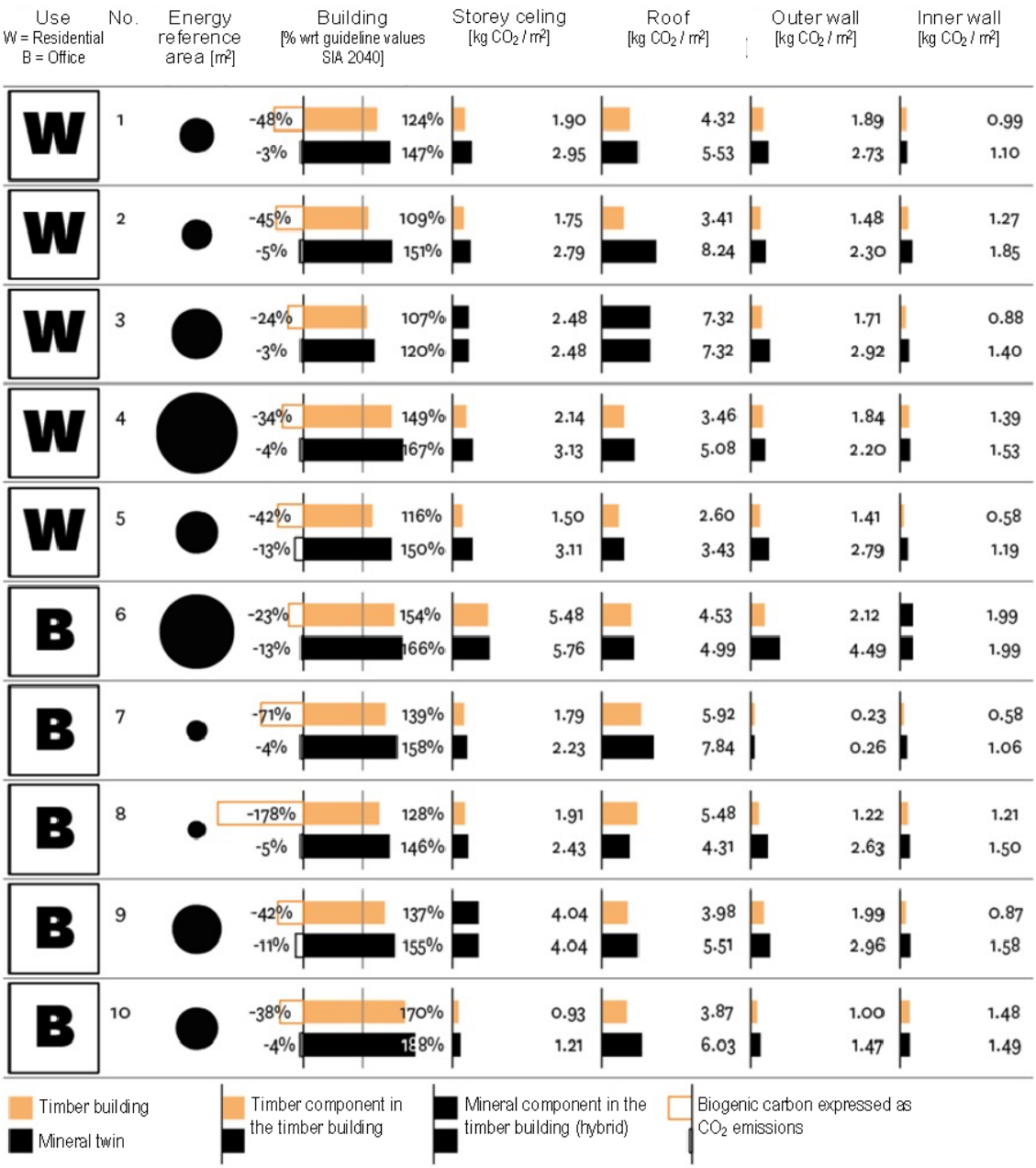


Figure 19: GHG emissions from 10 building examples (Lamster 2023, p. 10).

Note:
*The emissions values of the **buildings** are expressed in relation to the guideline values for grey GHG emissions of the SIA 2040: 2017 energy efficiency path (for residential and administrative buildings = 9.0 kg/m²a).*
*The emissions values of the **building components** refer to the square metre of component area.*
*The characteristic values of the **biogenic carbons** refer to the total value of GHG emissions of the respective building as released CO_2.*

In science and practice, the cascade utilisation approach has been applied since around 2006, i.e. wood should, whenever possible, always be used first as a material and at the end of its service life as a minimum for energy recovery in order to replace fossil fuels. With adequate planning, construction waste can therefore be avoided in timber construction compared to solid construction by reusing the components (Müller and Moser 2022). The substitution effect of reused timber components can be estimated at 0.51 tonnes of CO_2 per tonne of wood used (Suter 2016), which corresponds to 0.255 tonnes of CO_2/m^3 of secondary raw material with an average wood density of $0.5t/m^3$.

If the timber is utilised for energy rather than material purposes after dismantling, fossil fuels are substituted with an average substitution factor of 0.6 tCO_2e/m^3 of wood (Hofer et al. 2007), although this depends on the respective electricity mix and can therefore change over time.

If there are no wood or waste incineration plants as in developing countries, southern Europe or the USA, the wood must be landfilled. In addition to the increased land use they cause, landfills also emit methane and nitrous oxide.[18]

A further substitution in the area of insulation materials can be assumed, which reduces the grey energy of a timber house compared to a solid construction house, as petroleum-based thermal insulation materials are used less frequently in timber buildings compared to wood fibres or other bio-based thermal insulation materials (Müller et al. 2015).

Increasing the resilience and sink capacity of the forest
Timber construction can also provide benefits for the forest. To ensure that sufficient wood is available for timber construction in the long term and that the climate potential of the forest is optimally utilised, wood for timber construction must come from sustainably managed forests or from "climate smart forestry", as otherwise there is a risk of deforestation or forests being underused and overaged (Verkerk et al. 2020; Cooper & MacFarlane 2023). Under these conditions, forest health and the multifunctionality of the forest can be identified as further co-benefits of timber construction. Optimised "climate smart forestry" also leads to more wood regrowth, which means that more CO_2 is sequestered in the forest and more wood is available for construction (see Figure 16).

Underutilisation of the forest can lead to a higher risk of forest fires and susceptibility to pest infestation, which can therefore be reduced through better forest management (Rey and Thalmann 2017; Verkerk et al. 2020). In addition, CO_2 sequestration in the forest is highest when wood utilisation corresponds to forest growth (Rey and Thalmann 2017). The increased use of wood, especially in overaged forests or protection forests in Switzerland through regeneration, also has a positive effect on the climate resilience of the forest against extreme weather events, as old trees are often not as climate-resistant because spruce, fir, etc. can no longer survive in certain places due to increased periods of drought and other extreme weather events. The altitude at which these trees grow well is changing due to climate change, which can be taken into account by forest management.

Non-climate-relevant co-benefits

Reduced reliance on extractive raw materials
In addition, in contrast to non-biogenic building materials, construction timber has the advantage that, apart from the fossil raw materials currently used for adhesive production and metal based fasteners, no rocks and ores have to be mechanically removed from the ground (Ramage et al. 2017) and is the only CCS technology that grows back, which is why it is also called a "nature-based solution".

Increase in biodiversity
Old and dead trees contribute to biodiversity because they provide a home for other creatures – deadwood is also often left behind in forest management. Climate-appropriate forest management leads to regeneration and diversification because not only monocultures are planted. Better and climate smart forest management therefore also enables an increase in biodiversity.

Avoiding waste and promoting circular economy
The reuse of timber components is progressing rapidly, which is contributing to the establishment of the circular economy and improved resource efficiency in the construction sector (Müller and Moser 2022). In the context of the emerging circular economy and the long-term scarcity of resources, it can be assumed that the timber structures planned for dismantling today will be sent for dismantling and material utilisation in around 50 to 100 years at the end of their life. The quality of the reclaimed wood assortment that will be available in the future will be significantly better than that of the reclaimed wood currently available, which was installed several decades ago. Wooden beams are already being sold or leased on the market with a take-back guarantee and databases are being created with all the wooden construction elements used.[19]

[18] https://www.bafu.admin.ch/bafu/de/home/themen/klima/zustand/daten/treibhausgasinventar/abfall.html
[19] See for example https://derix.de/nachhaltigkeit-im-holzbau/nachhaltig-bauen-mit-holz/ and https://www.holzbauaustria.at/technik/2021/06/kreislaufwirtschaft-im-holzbau-beginnt.html

2.3.4 Risks

Durability/Reversal Risk
There is the risk of TCCS that carbon is not kept out of the atmosphere permanently but that it is released after dismantling the building, if construction timber is utilised for energy production without carbon capture or conversion into biochar. This leads to the stored carbon escaping back into the atmosphere. Thus, TCCS cannot be classified as a **permanent carbon removal** and there are reversal risks not only at the end of its service life but also due to fires before the planned end-of-life. There are different ways to address this risk, which depend also on the accounting approach used (see Table 1 and Section 2.1). Gupton et al. (2026) identify seven different methods for managing this risk, ranging from risk-transfer strategies – such as buffer pools, insurance, and carbon trust funds – through purchasing strategies such as vertical and horizontal stacking, to accounting approaches like risk-weighted and time-weighted accounting. To prevent the end-of-life risk, Frischknecht and Pfäffli (2023) make two proposals for making permanence legally binding in Switzerland:

- An entry in the land register is intended to ensure "that materials containing biogenic carbon are either reused, recycled or then permanently stored. In the event of recycling or reuse, the party that accepts the building materials/construction elements must enter into an analogous legal obligation" (Frischknecht and Pfäffli 2023, p. 31).
- A take-back guarantee and advance decommissioning fee can oblige manufacturers and suppliers to take back material from dismantled facilities. At the same time, the disposal of biogenic building materials without CCS will also be prohibited (Frischknecht and Pfäffli 2023).

Deforestation (leakage)
The prerequisite of sustainable forest management for timber construction as a negative emissions technology has already been explained. However, the risk of deforestation and overexploitation of forests must not be ignored, as this could lead to higher CO_2 emissions as well as losses of forest services such as biodiversity, air and water quality. In addition, the long-term sustainable supply of round timber for timber construction would not be ensured (P. Smith et al. 2019).

Shortages in the timber market
Wood will likely play an increasingly important role in the defossilisation of the heating industry, and demand will increase as hundreds of new heating networks are planned. Therefore, there is the risk of shortage in the timber market. However, the anticipated pressure on timber supply cannot be reduced to a simple competition between energy use and construction: the picture is considerably more complex. Raw timber availability depends on assortment-specific dynamics – sawlogs, pulpwood, and energy wood each follow distinct market logics – and structural constraints such as forest management capacity and persistent staff shortages in harvesting and logistics compound the challenge. Moreover, the pressures facing forests themselves, including climate-driven disturbances, pest outbreaks, and the need for active silvicultural intervention, mean that future timber mobilisation will increasingly yield lower-quality assortments rather than additional sawlog volumes suitable for structural construction. In this context, the risk is not merely that logs are diverted to combustion instead of sawmills, but that the overall quality profile of available timber shifts in ways that disadvantage the construction sector. Since heating networks represent inflexible, long-term infrastructure while construction retains access to alternative materials, the construction industry faces a compounded vulnerability. Appropriate framework conditions and regulations remain necessary to reflect the higher social benefit of wood in construction, but these must be grounded in a differentiated understanding of timber assortments and forest-sector realities.

2.3.5 Accounting

Three main approaches can be distinguished for accounting for carbon storage in timber construction, each reflecting a different perspective (see Table 1).

The **Harvested Wood Products (HWP) Pool** approach follows the **national inventory logic** (see Figure 20) and is since 2013 the basis of Switzerland's regulated CO_2 market ("Senke Schweizer Holz", Swiss Wood Sink). It uses the same inflow–outflow logic as the national GHG inventory: a project generates credits by increasing the inflow into the HWP pool relative to a business-as-usual baseline. Only Swiss wood – including Swiss products made from Swiss raw timber and exported products – is counted; imported wood products are excluded. This approach has operated for many years, the rules got adopted after independent evaluations by the Swiss Federal Audit Office - in particular the reference model. The generated certificates are not internationally tradable and this approach is incompatible with the EU Carbon Removal Certification Framework (CRCF), which favours object-level accounting.

The **object-level (building-level/project-based) approach** quantifies the biogenic carbon stored in a specific construction. It is the dominant model in voluntary carbon markets, with most standards having emerged in this space. Examples include Verra/VCS, CSI, HAFL/Post-CDR, Oncra, and Rainbow. These standards typically define a business-as-usual baseline using an average tCO_2e/m^2 for a conventional building, account for embodied emissions across lifecycle stages A1–A5, and issue credits for the difference. Storage periods of at least 35 years are generally required, but end-of-life – such as retirement or replacement of certificates upon demolition – is not appropriately addressed. This approach enables precise quantification, transparent ownership of storage rights, and internationally tradable units, and it creates direct incentives for developers and investors. However, it requires robust monitoring for reversals, a credible building-level baseline, and mechanisms to address permanence and end-of-life liability.

A not yet finalised approach proposed by the Swiss Post is the **value chain approach** that traces carbon flows from forest through processing to the final built structure. It is compatible with national GHG inventories (forest pool and harvested wood products pool) and allows mitigation and removal to be attributed precisely where they are achieved along the value chain. However, establishing a credible baseline is complex, as conditions evolve throughout the value chain, and the involvement of multiple stakeholders increases administrative burden. Nevertheless, a first pilot application of the approach has already been carried out in Switzerland in collaboration with the Federal Office for the Environment (FOEN) and the Burgergemeinde Bern, illustrating that the concept can be operationalised in practice.

In the individual projects / object level approach the emissions from harvest, transport, process, and construction are determined and subtracted from the carbon embodied in the products. The CO_2 content reflecting the mitigation potential in timber construction is standardised per tree species (softwood or hardwood). With such a system boundary including upstream emissions and removals in the forest sector, it becomes evident that increased timber use can also have a negative effect on forest's CO_2 storage. Negative impacts both on carbon stock and forests' carbon removal potentials as well as other sustainability dimensions must be minimized by dedicated monitoring and remediation measures in forest management (including through qualitative criteria and a risk assessment (Cooper and MacFarlane 2023). Risks of deforestation are expected to be particularly pronounced in the global south and not in the industrial forests, which are managed under strict forest laws. An additional possibility for identifying and managing deforestation risk is through the use of certification schemes such as FSC or PEFC.

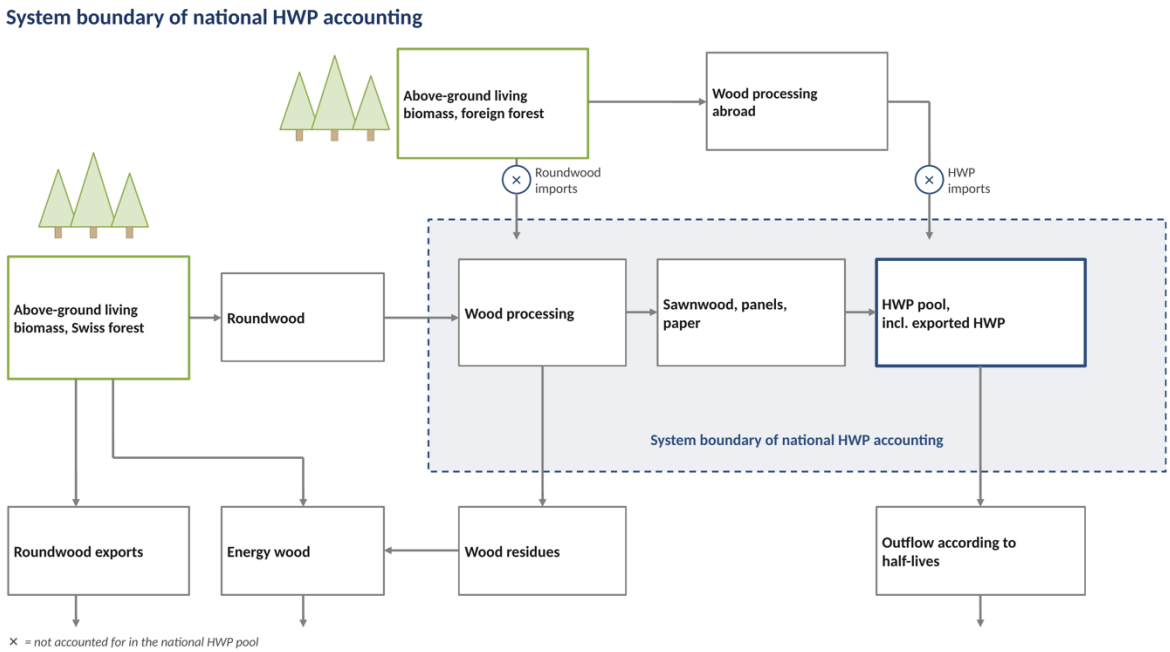


Figure 20: System boundaries for Harvested Wood Products (HWP). (Source: translated from Presentation of Christian Aebischer, FOEN, at DeCIRRA workshop 13.12.2024)

National GHG inventory accounting

In national GHG inventories, the use of timber in construction represents a form of the category *Harvested Wood Products* (HWP),[20] whereby increases in the carbon sub-pool are reported in the inventory – following IPCC guidelines (2019) (Rüter et al. 2019). The IPCC guidelines are currently revised and there may be changes to the HWP reporting.

For the reporting of HWP different methods are eligible under the Paris Agreement (Kayo et al. 2021). Switzerland uses the same approach as in Commitment Period 2 of the Kyoto Protocol which was based on the IPCC 2013 Guidelines (Intergovernmental Panel on Climate Change (IPCC) 2014). It is called Production approach as it accounts for products made from wood harvested in the reporting country. As such, these guidelines do not estimate the actual carbon stock in the reporting country, but the stock of products made from domestically harvested wood. Thus, an increase in HWP is a net-increase in the *stock* of harvested wood products (rather than on a metric of flow) and the in- and outflows into building-timber stock need to be monitored. It can increase if (1) aggregated at the national level more timber is harvested in forests or plantations, if (2) the average lifetime of HWP is increased or if (3) feedstock is reallocated from a product with a shorter lifetime to a product with a longer lifetime.

(1) Increased wood utilisation in forests can in principle be a good thing, but it also carries the risk of reducing the stock of standing biomass (see above in Section 2.3.4 on risks). For more Harvested Wood Products to result in an overall CO_2 removal, accelerated harvesting needs to be accompanied by growth-promoting practices, such as forest fertilisation, use of improved plant material, forest thinning and other management strategies such as the climate smart forestry mentioned above (Petersson et al. 2022): The HWP carbon pool and the living biomass carbon pool in the forest are interlinked, as the net carbon balance of wood is determined by the sum of carbon stock changes in forest and HWP pools.

(2) The second strategy – increasing the lifetime of HWP – through recycling or reusing biomass materials will extend the storage time of Carbon and offset longer living gases such as CO_2 emissions. In order for this strategy to be successful the IPCC Default Values will need to be amended, which is possible but needs national support and coordination.

(3) The third strategy (reallocating feedstock to longer-lived products) increases the lifetime of the carbon stock, yet there may be limitations as to the economic uptake capacity of such alternative product types. Perhaps the most extreme example of such a change is moving from timber for energy utilisation to utilisation of timber in construction. Willingness to pay and relative prices for the material substitution (prices of fossil + carbon prices compared to timber) play an important role in addition to policies, which may also support such substitution.

Accounting in carbon markets

International carbon markets have to date refrained from crediting sector-level changes in stock, and HWP-based removals and have thus not featured as such in compliance nor voluntary carbon markets to date. To date, there have also not been any accepted methodologies (Rainbow – Carbon storage in biobased construction materials) for the emissions-reducing effect of utilising HWP to displace higher-emitting alternatives. To include such project types in carbon markets, baseline and monitoring, reporting and verification (MRV) methods, as well as a strict due diligence process to avoid double-counting, would need to be developed and accepted by carbon buyers in a carbon market standard – yet it does not seem likely that sector-crediting or crediting of policies will become feasible in international carbon markets under the Paris Agreement any time soon. Another concern is the upstream displacement factors which are often based on static averages that may overstate real-world substitution benefits as markets and technologies evolve.

Recent developments, however, indicate a clear shift towards project-based crediting approaches for timber construction. Rather than addressing sector-wide changes, emerging methodologies focus on individual building projects, where carbon storage in biogenic materials can be quantified, monitored, and verified within a defined system boundary. In this context, voluntary carbon market standards are beginning to recognise biogenic carbon storage in buildings as a form of CDR, provided that storage duration, monitoring obligations, and reversal risks are adequately addressed.

Several methodological frameworks are currently under development or early implementation. For instance, Verra has explored approaches to account for both biogenic carbon storage and material substitution effects, although methodological approval and large-scale deployment remain pending. In

[20] A Harvested Wood Product is any type of product made out of harvested wood e.g. sawnwood, wood-based panels, paper and paper-board (see Kayo et al. 2021).

parallel, newer standards such as Riverse (Rainbow Standard) are operationalising removal-based crediting for timber buildings, including differentiated storage durations (e.g. 35, 50, 75 years) and corresponding monitoring and buffer requirements. These approaches are broadly aligned with ongoing regulatory developments under the EU CRCF, which emphasises durability, monitoring, and liability mechanisms for carbon removals.

Despite this progress, several challenges remain central to the integrity and scalability of timber-based carbon credits. These include:

- Additionality, particularly demonstrating that timber construction is not already standard practice and that carbon finance materially influences project decisions;
- Durability and reversals, given that carbon stored in buildings is not permanent and must be monitored over decades, with buffer mechanisms or insurance addressing reversals;
- Double counting risks, especially across the value chain (e.g. forestry, materials, and building-level claims) but also end-of-life;
- Baseline definition, including robust and reproducible “mineral twin” approaches to model counterfactual buildings; and
- Data availability and MRV, requiring detailed and verifiable material inventories, supply chain documentation, and long-term monitoring frameworks.

In this context, digitalisation plays a critical enabling role. The integration of building information models (e.g. IFC-based workflows), automated quantity take-offs, and standardised databases (e.g. EPDs and national LCA datasets) can significantly reduce transaction costs and improve transparency. Digital tools also facilitate the development of counterfactual baselines, allowing for systematic comparison between timber buildings and conventional alternatives in terms of cost and emissions, thereby supporting additionality assessments.

Overall, while carbon markets have historically not captured the mitigation potential of timber construction, current methodological and regulatory developments suggest that project-level crediting of biogenic carbon storage in buildings is becoming increasingly feasible, provided that robust accounting, monitoring, and risk management frameworks are in place. The volume of such credits will depend on MRV costs, how durability and end-of-life are addressed, and how prices of other removal credits develop.

Accounting approaches and insights from LCA

Expectations regarding the necessary conditions for monitoring, reporting and verification (MRV) methodologies are evolving with some methodologies in development as mentioned. There is not yet a clear consensus on how to account for TCCS: neither at the project level nor at the national level of HWP sub-pools is this done consistently. Insights from LCA and broader debates on the necessary conditions for accounting of removals from wood products can therefore help inform any methodology developments to determine the carbon removal results from timber construction. Expectations flowing from international discussions on removals notably include the following four points (Tanzer and Ramírez 2019):

1. GHGs are removed from the atmosphere and durably stored.
2. GHGs removed are stored permanently (there is no agreement whether a time-limited permanence may be acceptable (e.g., 30 years or 100 years).
3. All emissions occurring throughout the value-chain are subtracted from the stored carbon.
4. The total amount of CO_2 stored needs to exceed emissions to achieve removal.

The study from Tanzer and Ramirez (2019) is considered an important definitional basis for developing removal-related methodologies in the EU.

When it comes to accounting for individual projects (rather than a sub-sector carbon-pool) the definitions of carbon removal and the LCA perspective require that the storage of Carbon must be monitored – which means applying an even larger system boundary: cradle-to-grave. Current project-level methodologies account only for the initial service life of the building, with the durability of carbon storage defined by this period. Depending on the building typology, this typically and conservatively ranges from 50 to 100 years. There are ongoing international efforts to account for the NET from timber construction[21] and accompanying research examines the validity of existing approaches in the voluntary carbon markets as well as the extent to which the national GHG inventory accounting guidelines may be built-upon for future crediting of such activities.

[21] See e.g., https://op.europa.eu/en/publication-detail/-/publication/d8185ac9-cc06-11f0-8da2-01aa75ed71a1

2.3.6 Estimates of costs, potentials, and main drivers

Costs

Several studies have analysed the cost competitiveness of timber construction in comparison with conventional mineral construction. From the perspective of negative emission technologies, the relevant question is not only whether timber buildings are more or less expensive at the level of total construction costs, but also what additional costs may be associated with the additional biogenic carbon stored in engineered timber products.

Recent Swiss evidence suggests that timber construction should not be described as systematically more expensive than mineral construction. Instead, cost differences are highly project-specific and depend on building typology, design quality, degree of standardisation, structural grid, fire and acoustic requirements, procurement strategy, and the level of experience of the planning and execution team (Wüest Partner 2024; Nötzli et al. 2025).

The most recent Swiss cost benchmark for residential buildings is the Wüest Partner study commissioned by Lignum and FOEN. The study analysed 17 realised residential timber buildings in Switzerland and compared them with a reference dataset of almost 50 mineral residential buildings. The results show that optimised timber residential buildings can be close to cost-competitive with comparable mineral buildings. For example, the 70%-quantile of the lower-price timber segment amounted to CHF 5,144/m² main usable floor area for Building Cost Classification 1–5, only slightly above the corresponding value of CHF 5,002/m² main usable floor area for mineral residential buildings (Wüest Partner 2024).

This is consistent with recent practitioner evidence from the City of Zurich. Interviewed market actors estimated timber-related additional costs at around 5–10% of shell-construction costs, corresponding to less than 2–3% of total building costs. Additional costs below 5% of shell-construction costs were considered achievable where timber construction is integrated correctly from the earliest planning phases (Nötzli et al. 2025).

Internal case-study analyses indicate that additional costs vary significantly between element groups and product choices. The highest differences tend to occur where timber products are used in highly loaded structural elements or where additional requirements for fire protection, acoustics, vibration, visible surfaces, or product origin apply. Conversely, timber can become more competitive where prefabrication, modularity, short construction time, standardised grids, and efficient spans are exploited from the outset (Timber Finance Initiative 2023). Figure 21 illustrates the additional timber construction costs at the level of the building cost plan for high-rise buildings. The costs depend on the product selection in the element groups of main group C “Building construction”. The maximum cost differences arise in the choice of load-bearing columns, while the smallest cost differences occur in the ceiling construction.

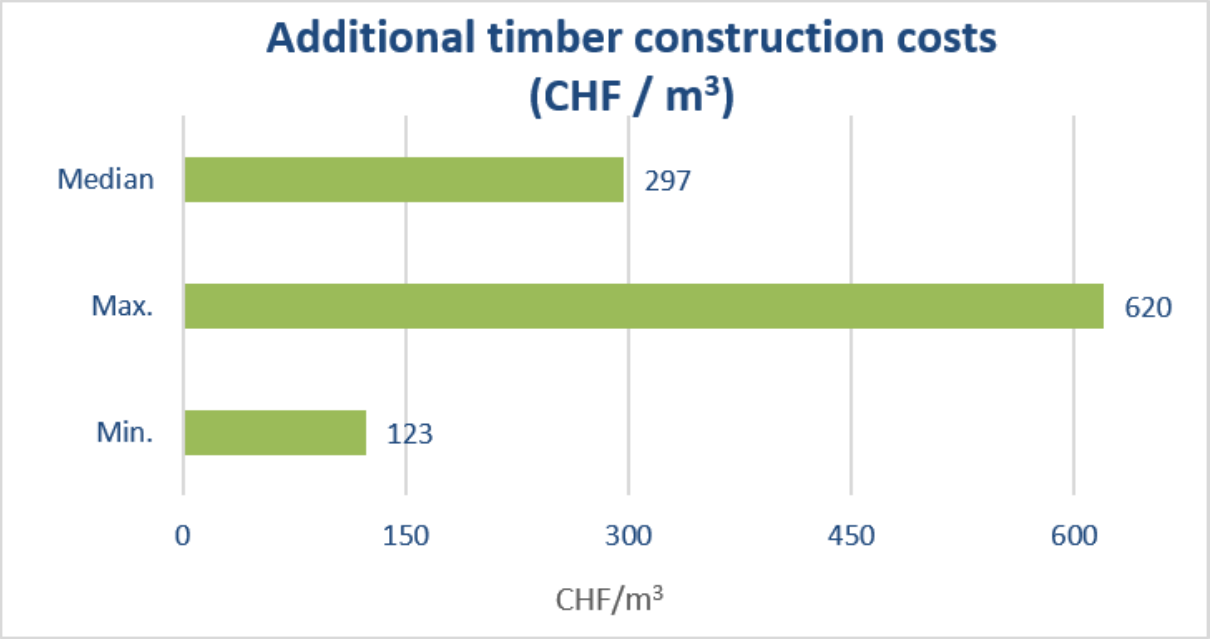


Figure 21: Additional timber construction costs for installed building products in the load-bearing structures compared with the traditionally used and functionally equivalent quantities of solid building products steel 235 and concrete C25/30 (own unpublished calculations, Timber Finance Initiative 2023).

Overall, recent Swiss evidence points toward a decreasing and increasingly project-specific cost premium for timber construction. As timber expertise increases among developers, planners, engineers, and contractors, and as procurement and prefabrication processes become more standardised, the cost gap between timber and mineral construction is expected to narrow further. At the same time, timber construction may offer additional economic advantages through shorter construction times, reduced weight, suitability for densification and extensions, and improved cost certainty due to early detailing and prefabrication (Wüest Partner 2025). Furthermore, it should be emphasised that decarbonising concrete – by whichever technology route, be it clinker substitution, alternative binders, or CCS-equipped cement plants – comes at a rising cost: low-carbon concrete will be more expensive than the conventional material it replaces, which will close the gap further. At the same time the baseline will need to be adopted and the mitigation effect from substitution will be lower than today Brunet-Navarro, et al 2021)

Potentials

The choice of building materials for the load-bearing structures of multi-storey buildings is dominated by the cement and steel industry in Switzerland and worldwide. Switzerland leads the world with a timber construction quota of 15%, compared to only 0.5% globally (Churkina et al. 2020). Although 15% of multi-family houses (MFH) in Switzerland are realised with a load-bearing timber structure, the conventional building materials like cement, steel and brick have a market share of 95% in the overall construction sector, so that the proportion of timber construction is less than 5%.[22]

First of all, it must be mentioned that the potential of timber construction is limited by two factors, namely, by the availability of timber and by the cyclical nature of construction activity and the rate of new and renovation projects. However, timber construction is one of the most scalable CMAs available to Switzerland due to the advancing use of this technology and existing infrastructure in production and processing. Currently, Switzerland is not reaching its timber construction potential, as the emission-intensive materials S235 and C25/30 are still used in 95% of load-bearing structures.

The potential of timber engineering with sustainable forest management is calculated in this report using two scenarios, which are shown in Figure 22. The first scenario "CH timber" shows the timber construction potential with the use of exclusively Swiss timber in the supporting structure. The second

[22] https://baumeister.swiss/modernisierungsoffensive-des-gebaeudeparks-muss-sich-auf-alle-baustoffe-abstuetzen/

scenario "CH building stock" shows the maximum use of wood, including imports, in the Swiss construction sector.

The "CH timber" scenario is dependent on Swiss timber harvesting and processing. The Swiss forest stock has continued to increase in recent years, with an average growth rate of 10 million m^3 per year. The current timber harvest of 5.9 million m^3 per year is around 30 % below the economic harvesting potential. As a result, forest owners are faced with the challenge of overaged forests that are increasingly exposed to climate change. Currently, approx. 37% (2.2 million m^3) of the timber harvest is used for logs, which can be processed into approx. 653, 000 m^3 of construction timber. However, only approx. 211,450 m^3 of glued laminated timber was produced in Switzerland in 2025 (Holzindustrie Schweiz 2025).

Up to 8.5 million m^3 of wood can be extracted from the Swiss forest, while at the same time strengthening the health and multifunctionality of the forests and storing up to 1.2 Mt CO_2e/year in construction by prioritising the use of Swiss wood as construction timber.[23] By 2050, a cumulative total of 36.08 Mt CO_2e could be stored with the maximum use of Swiss wood in construction (FOEN 2022).

Scenario 2 "CH building stock" calculates the maximum use of wood in the building sector. This is based on the study by Savi and Klingler, in which the maximum use of wood in construction requires 8.3 million tonnes of freshly harvested wood (Savi and Klingler 2022). This corresponds to an annual potential consumption of approx. 4.5 million m^3 of construction timber in the Swiss construction sector. Timber construction would have to be promoted with immediate effect. Assuming that the potential of the building sector is fully utilised in 2050, a cumulative 103 Mt CO_2e will be stored in construction over the long term. This corresponds to an annual CO_2 storage of 3.52 Mt CO_2e, meaning that the annual storage can be almost tripled through imports.

The "CH timber" scenario utilises the potential of the Swiss forest by 2050. The scenario can provide the construction sector with approx. 1.2 Mt CO_2e/year. However, this requires investments in forest management and the subsequent processing stages. This applies in particular to the material utilisation of hardwood, 70% of which is currently used for energy. In the "CH building stock" scenario, the capacity of the Swiss forest is obviously exceeded. Around 75% of construction timber is currently imported (FOEN 2022). If Switzerland wants to utilise the entire timber construction potential of the construction sector, the availability of timber in Switzerland must increase significantly, as in the "CH timber" scenario, and yet approx. 65% of construction timber must still be imported. Figure 23 shows the cumulative quantity of Swiss and imported wood.

Both scenarios are based on the optimal use of wood and require prioritised material recycling of wood. It must be ensured that the construction timber is stored in the building for the long term and that the durability criteria of at least 100 years are met. However, both scenarios require measures in the forest, promotion of the entire forest and timber chain, promotion of the demand for timber construction, sensitisation of investors and continued high quantities of imported construction timber.

The present calculations and simulations refer to the current timber harvest and do not yet include potential changes in forest productivity resulting from Climate-Smart Forestry measures, such as adaptive silviculture, site-appropriate tree species selection, mixed stands, active regeneration, and measures to increase forest resilience. Such measures may help maintain or increase forest growth and carbon sequestration under changing climatic conditions, while also supporting the production of wood for long-lived construction products. However, the magnitude of this effect is highly site-specific and should be based on explicit forest growth scenarios rather than generalised assumptions (Nabuurs et al. 2018; FOEN & WSL 2025). As Figure 24 illustrates, annual growth per hectare depends on tree species, site conditions, stand age, and management regime. Since tree growth is linked to carbon uptake, forest management strategies should aim to balance carbon sequestration, climate resilience, biodiversity, and the production of timber dimensions suitable for the construction industry.

[23] The economic timber harvesting potential is approx. 8.5 million m^3. Currently, approx. 5.5 million m^3 are harvested. The remaining 3 million m^3 remain in the forest and with a value-added factor of approx. 0.4 per m^3, an additional construction timber potential of 1.2 million m^3 is assumed (0.4 * 3 million m^3). However, not all resources can be activated immediately. Active forest management must be implemented, the industry must grow and investments must be made in infrastructure.

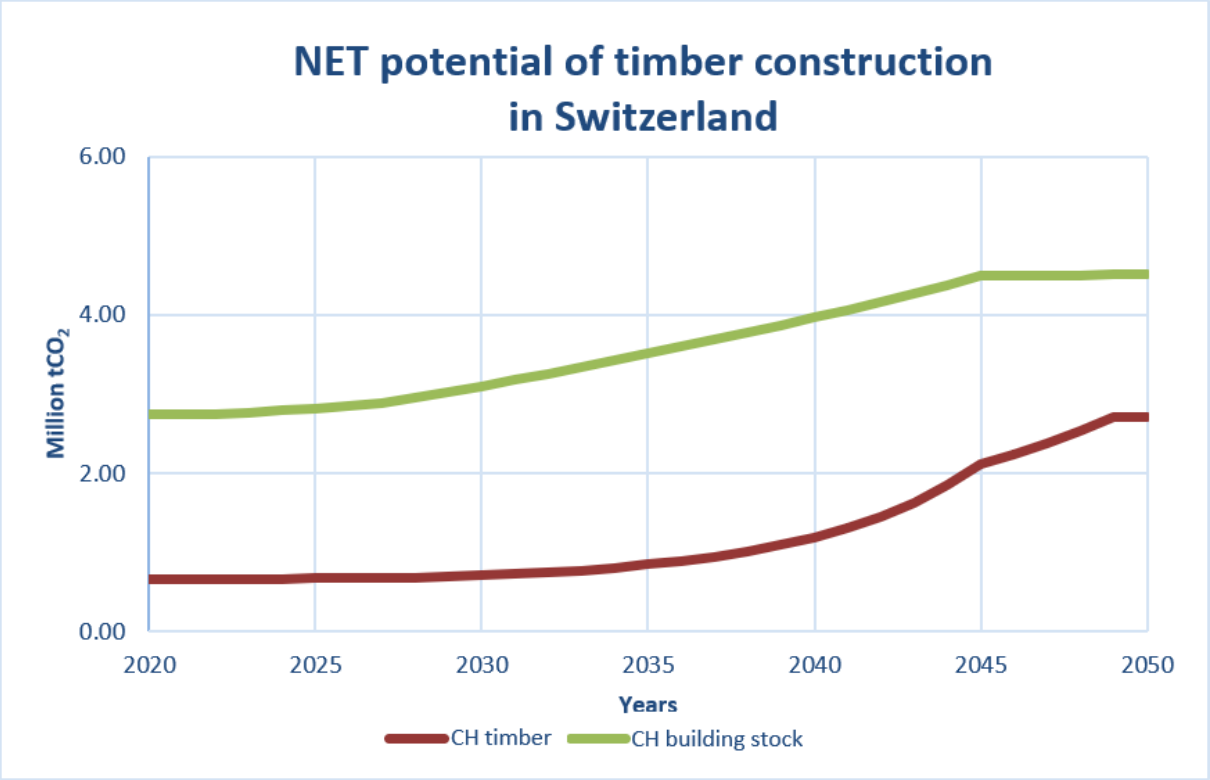


Figure 22: Comparison between the scenarios CH timber in construction (brown) and CH building stock (green). The potential of the building stock corresponds to the maximum use of wood construction in the Swiss construction sector (own graph by Timber Finance Initiative 2023, based on data from Habert et al. 2022 and FOEN 2022).

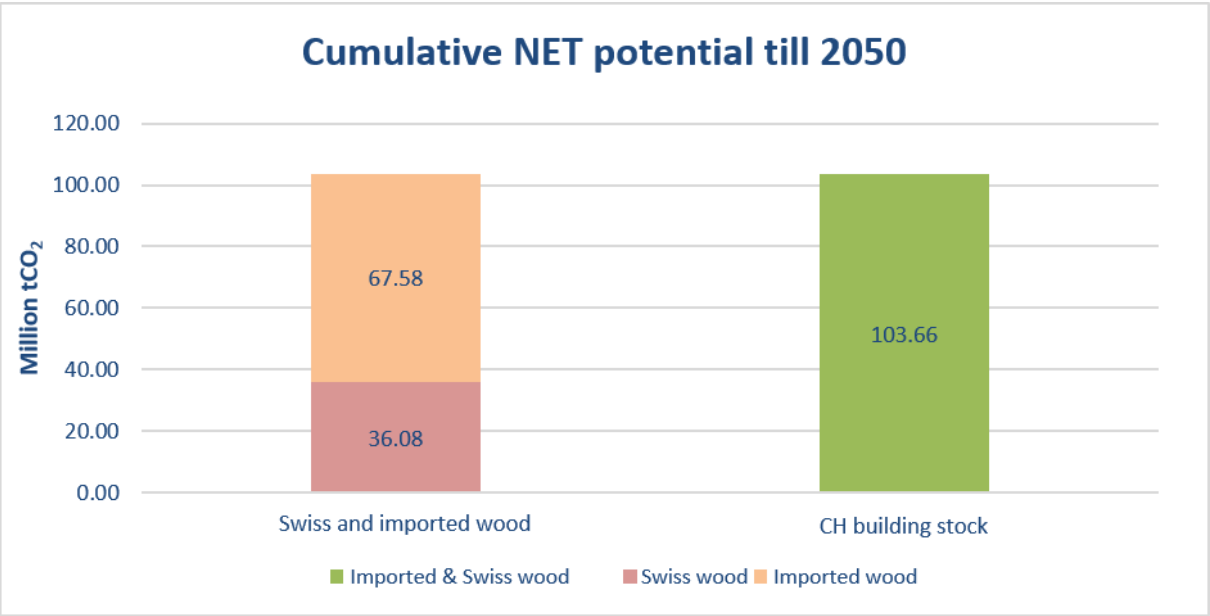


Figure 23: Cumulative potential of the buildings sector: approx. 65% of the timber required for construction is imported (own unpublished calculations, Timber Finance Initiative 2023, based on data from Habert et al. 2022 and FOEN 2022).

In the context of Swiss GHG emissions of approx. 46 Mt CO_2e/year, timber construction could save approx. 10% with immediate effect with maximum funding (scenario 2 "CH building sector"). This does

not include the co-benefits from the substitution of other building materials and the higher sequestration rate in the forest.

In addition to financing instruments and policies, investment capital must also flow into the timber industry chain in order to be able to process the additional supply of Swiss timber and thus maximise the timber construction potential. The increase in the supply of and demand for timber construction must continue to be supported financially and the demand from investors must be additionally promoted through knowledge transfer and the provision of timber construction expertise.

The potential of TCCS can be summarised as follows (S. Flückiger, presentation at S-WIN winter conference on 26 January 2023, unpublished):

- Swiss forest area: 1.31 million hectares
- Usable Swiss forest area: 0.655 million hectares
- Current growth in Switzerland: 8.5 m^3/ha/y or 4.7 million m^3/y
- Climate Smart Forestry growth: 17 m^3/ha/y or 9.5 million m^3/y
- Stock in Switzerland: 374 m^3/ha (battery is almost full)
- USP and potential of the forest lie in growth.

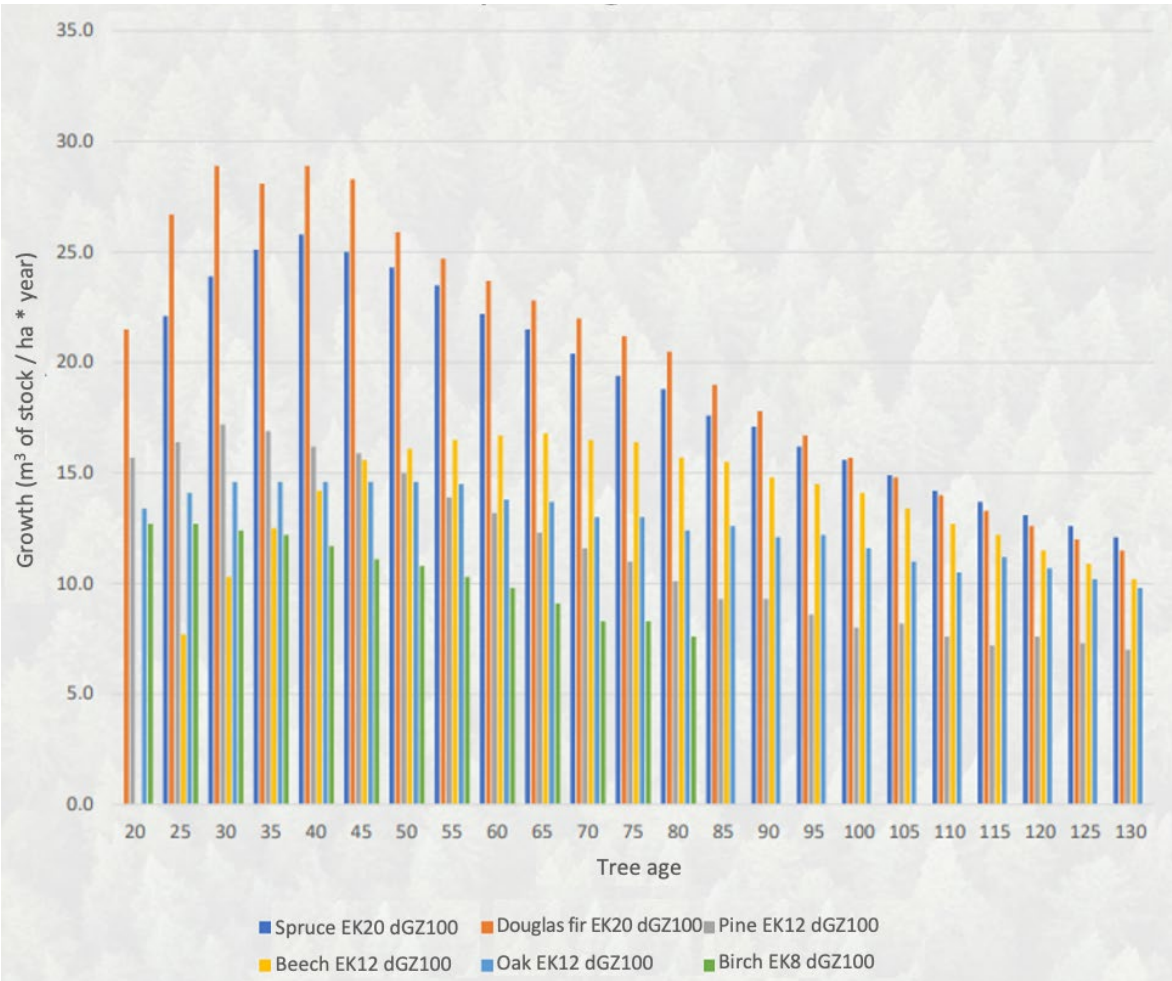


Figure 24: Tree species growth table (Forest Research Centre Freiburg).

Note: EKX = yield class with growth of X solid cubic metres per year and hectare; dGZY = with an average total growth over Y years. Example based on the tree species spruce EK20 dGZ100: The spruce grows an average of 20 cubic metres per year and hectare within 100 years. With a tree age of 45 years, the increment is 25 cubic metres per cubic metre per year, whereby the cubic metre of stock is defined as the circular area of the tree at breast height multiplied by the tree height and the tree species-dependent form number.

2.3.7 The role of TCCS across scenarios

Carbon storage in wooden construction is utilised (almost) to its maximum potential – 2 Mt CO_2/year is assumed from Swiss and imported wood – in every scenario (see Figure 25). This is because it represents a cost-effective CMA that is already available today and independent of CO_2 transport infrastructure or geological storage sites. TCCS is therefore considered a no-regret option.

This maximum assumed potential is consistent with Priore et al. (2025), whose modelling puts annual biogenic carbon storage in Swiss buildings at up to 2.5 Mt CO_2 by 2050. Their scope is broader, it includes renovations and covers both structural timber and non-structural bio-based materials such as straw, grass, hemp and wood-fibre insulation as well as wood-based finishings. As Priore et al. (2025) show, the result is sensitive to the assumed renovation and demolition rates. Under high demolition, more biogenic carbon enters the building stock in the short to medium term, because more bio-based construction is needed to replace what is torn down; as those bio-based materials themselves begin to be demolished, however, the advantage erodes quickly, and over the long term the low-demolition scenario stores more carbon in total. How much of this counts as TCCS then depends on the end-of-life assumptions: our modelling assumes that combustion plants at the end of the cascade are equipped with CCS, which makes long-term storage more likely.

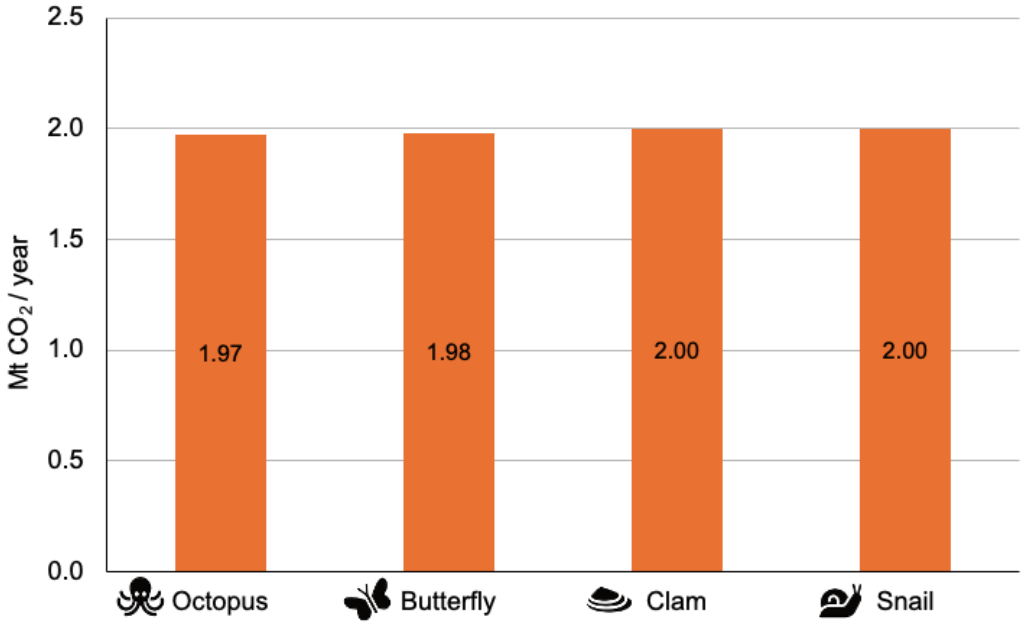


Figure 25: Use of wood in construction within Switzerland in the DeCIRRA scenarios (Mt CO_2/year).

2.3.8 Relevant actors

The players relevant to TCCS were identified by means of stakeholder mapping. The timber construction scene in Switzerland, which is characterised by small and medium-sized companies, is very well established thanks to its long history spanning many generations with many players. Since the "Wood transition 2020", it is well positioned for new challenges thanks to rising prices, the generational change in owners who are active at every stage of the value chain, good environmental awareness, a drive for innovation and active institutions that manage the entire chain from a higher-level perspective.

The following actors have been identified as drivers for the development and establishment of TCCS in Switzerland:

- **Federal Office for the Environment** (FOEN): The FOEN offers knowledge transfer and funding through its Forestry Department and the Wood Action Plan. It is committed to the material use of wood in construction as a Carbon storage medium.

- **Companies and organisations** along the entire forest and timber (construction) value chain that can act as multipliers with regard to knowledge transfer, communication and compliance with sustainability standards and calculation standards with regard to carbon storage in timber construction:
    - **Swiss Wood Innovation Network** (S-Win), which supports the exchange between research institutions and construction companies in timber construction.
    - **Lignum**, which supports the timber construction industry by providing technical principles and guidelines for timber construction.
    - **Holzbau Schweiz** is committed to the increased use of wood in construction.
    - **Swiss Timber Engineers** is the association of timber engineers that ensures the transfer of knowledge from research to practice.
    - **Wald Schweiz** (Swiss Forest) is the association of forest owners and campaigns for framework conditions that allow forestry companies to manage Swiss forests in an economically and ecologically sustainable manner.[24]
    - **SIA** is the Swiss Society of Engineers and Architects, which, among other things, develops standards in the construction sector and provides them to practitioners. SIA is an important multiplier for any standards relating to permanence and carbon storage in timber buildings.
    - **Minergie** Its Eco standard offers a harmonised approach and incentive for net-zero calculations, supported by certification labelling and a positive impact on future property values.
    - **Verein Senke Schweizer Holz** (Swiss Wood Sink Association), which connects around 150 sawmills and wood-based panel producers who are committed to increasing the provision of woodmaterials as a Carbon sink.
    - **Verein Wald-Klimaschutz Schweiz** (Swiss Forest Climate Protection Association) supports CO_2 sink projects in the forest.
    - **Timber Carbon Solutions AG**, markets durable high integrity Timber Carbon Removal Credits under an ICROA/ICVCM endorsed methodology derived from the built environment. These are backed by a robust, vertically integrated supply chain spanning sustainable forestry, timber construction, and real estate.
    - **Treeze** specialises in the life cycle assessment of building products and works with various institutions to develop scientific publications on the accounting and calculation of CO_2 storage capacity in timber construction.
    - The timber construction companies united in **industry associations** such as **HIS**.
    - Timber construction engineering companies such as **Timbatec**, **Pirmin Jung**, etc., which develop timber construction in collaboration with science (ETH, EMPA, BFH).
    - **Wüest Partner**, which carries out studies on timber construction potential and costs on behalf of FOEN, which are aimed at major investors.
    - **Foundation for Climate Protection and CO_2 Compensation (KliK)**, which can contribute to the financing of wood sink projects.
    - **EMPA** is the Swiss federal Laboratories for Materials Science and Technology and part of the ETH Domain. It conducts interdisciplinary applied research in areas such as sustainable construction, materials science, energy systems, and environmental technologies, supporting innovation transfer between academia, industry and public institutions.
    - Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren (**KBOB**): They publish life cycle assessment (LCA) data for the construction sector.
    - **Post CDR AG**: They are active in developing methodologies and CDR projects including for forest and wood utilisation.

- Various **Swiss universities**, particularly the following, have been identified as important players in the provision of knowledge:
    - In addition to life cycle analyses, **ETHZ** and **PSI** also develop the basis for the development and testing of building materials.
    - The **Bern University of Applied Sciences** BFH is also working on the fundamentals of building materials and analysing the use of wood in Switzerland.
    - **WSL** develops and analyses future forest management scenarios and their impact on possible developments in timber construction.

- **Administration**:

[24] https://www.waldschweiz.ch/de/verband/wer-wir-sind

- The **City of Zurich**, Office for Buildings, is actively involved in the development and investigation of the basis for potentials and crediting methods with regard to timber construction as carbon storage.

2.3.9 National and international policies and incentives

In Switzerland

The Forest Act foresees in Art. 34 b the promotion of the use of sustainably produced timber for the construction of federal buildings. Apart from this article, we are not aware of specific policies to support the use of timber in construction in Switzerland. Nonetheless, given that the recently adopted Federal Act on Climate Protection Goals, Innovation and Strengthening Energy Security[25] foresees that the federal administration shall act as a role model and achieve net-zero emissions by the year 2040 and that the cantonal administrations shall strive to achieve the same goal (KIG, Art. 10), and given that the revised Federal Act on Public Procurement as well as the corresponding Ordinance[26] give more weight to sustainability and to the compliance with environmental law, it seems likely that more instruments to support sustainable buildings within public procurement will be adopted.

For example, a platform for knowledge exchange on sustainable public procurement[27] has been established. Furthermore, some local governments are starting to establish sustainable construction requirements: All new government buildings in the city of Zurich are required to comply with the green building standard Minergie-Eco, which includes an embodied carbon performance target for certain building types (Think Wood 2021). In addition, the city has established a 2050 target for embodied life cycle carbon in residential buildings.

In April 2026 a new Minergie Net-Zero standard was released which certifies buildings that cause very low greenhouse gas emissions (GHGE) over their life cycle. Once the life-cycle emissions have been determined, the carbon stored in the building is subtracted from the remaining emissions and thereby reduces the building's greenhouse gas balance. The residual emissions are then offset using removal certificates from biochar, sourced 50 % from Switzerland and 50 % from Portugal[28].

Another approach is the parliamentary initiative to "strengthen the circular economy", enshrined in an amendment to the Swiss Environmental Protection Act (EPA) adopted in 2024: The Federal Council is granted the authority to establish requirements for resource-efficient construction (EPA, Art. 35j), but remained shy of adopting limit values for grey GHG emissions in buildings. Furthermore, building upon the administration's role model established under the KIG, and upon EPA art. 35j, the Motion 25.3422 from 1st April 2025 tasks the Federal Council to define guidelines to promote the sustainable production of building materials (including wood) through public procurement, including an eligibility and award criteria such as CO_2 emissions during manufacturing or recyclability.[29]

In 2017 a timber in construction project[30] was carried out within the national research program NFP 66, where some recommendations were made, but there seems to be no resulting policies yet.

In addition to federal and local initiatives, requirements related to embodied energy and GHG emissions in buildings are also increasingly addressed through Swiss building standards and cantonal energy regulation. The MuKEn – the Model Regulations of the Cantons in the Energy Sector – provide a harmonised basis for cantonal energy requirements and are progressively taken up in cantonal legislation. While their primary focus has traditionally been operational energy, recent developments show a growing attention to the environmental impact of construction materials and embodied emissions. As part of the initiative to strengthen the circular economy, and to create incentives for environmentally friendly construction methods, cantons have been tasked with setting limits on grey energy for new buildings and for major renovations of existing buildings as part of the MuKEN (Energy Act, Art. 45, para. 3e). In parallel, SIA 390/1 provides a Swiss methodology for assessing GHG emissions over the life cycle of buildings and supports a more systematic consideration of both operational and embodied emissions in planning and decision-making. How strong the incentive created by the new MuKEn 2025 will be depends on the limit value, or SIA efficiency pathway, of the SIA 390/1 standard that the cantons choose, and on how steep the reduction pathway is. The lower the permitted

[25] https://www.fedlex.admin.ch/eli/cc/2023/655/en
[26] https://www.fedlex.admin.ch/eli/cc/2020/126/de and https://www.fedlex.admin.ch/eli/cc/2020/127/de
[27] https://www.woeb.swiss/de/
[28] https://www.minergie.ch/de/zertifizieren/minergie-netto-null/
[29] https://www.parlament.ch/de/ratsbetrieb/suche-curia-vista/geschaeft?AffairId=20253422
[30] https://www.nfp66.ch/de/Ws1uasKdbEmHileQ/seite/ergebnisse

embodied emissions and the more steeply they decline over time, the stronger the incentives for timber construction in both renovation and new build. Thanks to its flexibility in adapting to existing materials and forms, timber offers major advantages, particularly in renovation. These instruments show that requirements for grey energy and GHG emissions in buildings are not only emerging internationally but are also increasingly being defined within the Swiss regulatory and standardisation context.

Beyond these policy measures and research initiatives, several standards are under development which seek to remunerate the climate performance of harvested wood products and timber use through mainly voluntary carbon-market mechanisms. The DeCIRRA project compared the relevant methodologies and standards; Table 5 provides an overview.

Table 5: Overview of different TCCS standards and approaches of voluntary carbon market.

Parameter / criterion	Verra / Verified Carbon Standard (TimberCarbon)	Carbon Standard International (CSI)	Oncra	Rainbow
System boundary	Timber load-bearing structure; building level.	All long-lived building materials with a biogenic carbon content and an expected service life of at least 35–60 years.	Bio-based materials in the primary and secondary structure as well as in insulation. Focused on the building level.	Bio-based materials in the primary and secondary structure as well as in insulation. Certification of individual building elements or of complete production lines.
Baseline / reference development: what would have happened without the project?	ER: mineral twin, business-as-usual construction. CR: average HWP stock (half-life ≈ 35 years) as reference; the project retains around 80 % after 100 years.	No explicit baseline is defined. In future, a standardised baseline will be updated every five years (v2).	BAU building, calculated average in tCO_2e/m^2 (non-biogenic). Business as usual (country-specific; no detailed calculations have been published).	BAU building, calculated average in tCO_2e/m^2 (conventional materials).
Additionality: covering both financial and regulatory additionality	Regulatory additionality; investment and market barriers are assessed.	The use of biomass must be additional and must not displace existing sinks. Demonstrated in the risk assessment.	No BAU evidence required; not mandatory; investment or innovation barrier.	The project must demonstrate bio-based production or application beyond BAU.
Project emissions	GHG emissions from modules A1–A3 (see Figure 17) are accounted for.	GHG emissions from modules A1–A5 (see Figure 17) are accounted for.	GHG emissions from modules A1–A5 (see Figure 17) are accounted for.	GHG emissions from modules A1–A5 (see Figure 17) are accounted for.
Leakage: increase in GHG emissions outside the project attributable directly or indirectly to project activities	Transport (LCA module A4), demand shifts and upstream substitution are accounted for.	Leakage and risk assessment are examined and validated in the Project Design Description; resulting emissions are accounted for and offset with geological carbon sinks.	Limited treatment; focus on carbon storage.	Reliance on project documentation.
Calculation of the storage performance	ER: baseline (mineral twin) minus project (timber construction) including the biogenic carbon store. CR: wood products in the building, calculated via half-life decay and storage duration. Currently only 21 years of certification, with corresponding deductions.	The global cooling effect is calculated using the Construction C-Sink tool on the basis of established LCA methods (EN 15804); all emissions from production (including far-reaching carbon-sink materials) and transport must be offset prior to registration.	CR: quantifies biogenic carbon in materials and buildings; applies a 100-year equivalence factor for shorter service lives.	ER: avoidance of embodied emissions / carbon storage impact; credits based on bio-based materials sold and installed.
Storage duration and end of life	Monitoring over a period of 100 years; liability mechanisms in the event of reversals.	Biogenic carbon is regarded as temporary (> 35–60 years); alternatively, permanently pyrolysed biomass in a concrete matrix (1,000+ years). Following demolition or combustion, certificates are retired or replaced; where material is reused, storage can be continued.	> 35 years, aligned with EPD specifications.	Storage > 35 years; removals > 100 years.
Monitoring, reporting and verification (MRV)	Monitoring of the building using satellite imagery.	Endorsed MRV system.	A register linked to the municipal building authorities that reports all changes.	–
Double counting of a certificate: the same carbon is	The baseline HWP cover all potential carbon pools in order to avoid overlaps; unambiguous assignment of ownership via the VCS registry.	Carbon sinks are recorded with a unique ID and geo-coordinates in the Global C-Sink Registry; before registration it is verified	Protocol and registry rules; separation from the land-use sector.	Protocol and registry rules; separation from the land-use sector.

Parameter / criterion	Verra / Verified Carbon Standard (TimberCarbon)	Carbon Standard International (CSI)	Oncra	Rainbow
sold or claimed more than once		that the sink has not already been sold elsewhere.		
Sustainability	Co-benefits assessed against the global SDGs and environmental integrity objectives; sustainability safeguards.	Only carbon-neutral, sustainably produced biomass is permitted; requirements based on FSC/PEFC, the World Farm Standard and the Biochar Standard.	Basic requirements regarding origin and documentation.	General sustainability requirements for bio-based materials.
Voluntary (VCM) vs. regulated market	VCM (Verra VCS); applicable worldwide, not yet approved	VCM; operated by Carbon Standards International AG (Switzerland).	VCM via the ONCRA registry; focus on Europe, but open.	VCM via the Rainbow and partner registries.
Advantages	Consistent with the 100-year permanence approach; clear baseline; focus on the building sector.	Continuous monitoring and control of effective carbon pools. Treats the building as a carbon sink, incorporating both temporary and permanent removals.	Simple storage metric; easy to apply at project level.	Suited to supply chains; applicable for manufacturers.
Disadvantages	Complex parameters; requires robust monitoring for reversals and end of 2025 in the approval process.	Building service life is difficult to calculate (owing to the diversity of materials); baseline, leakage and additionality are not well defined.	Not ICROA/ICVCM-endorsed.	Methodology was end of 2025 still under development; many points still being elaborated.

Note: BAU = Business as Usual; CR = Carbon Removal; ER = Emission Reduction; VCM = Voluntary Carbon Market. Comparison with Post value-chain approach, CarbonLänd, CRCF can be found here: https://docs.google.com/spreadsheets/d/1AVhc7kSjSC-zRexJ9Jv5EJiM6zau9ELj_he46G846gY/edit?usp=sharing

In Switzerland there is a compliance scheme that has been implemented together with the Swiss Wood Sink Association since 2014, for which around 4.38 million certificates have been issued as of 2025. This is an industry-level project and the revenue from the sales of certificates benefits Swiss sawmills and raw wood processors. The project accounts for additional changes in carbon storage in harvested wood products, following an accounting logic aligned with national GHG inventory reporting. It does not account for storage at the level of individual buildings but rather compensates for additional changes in the harvested wood product carbon pool (Figure 20).

In theory the project can include measures in Swiss forests, in the processing chain (e.g. investments in new saws) and downstream towards end customers. In this sense, it should be understood as a sectoral or industry-wide approach along the forest and wood value chain, rather than as a building-level certification system. However, most of the projects in the past were related to investments in the wood industry not in the forest.[31] Duration of the storage is therefore discussed in a different context than in project-based temporary carbon storage approaches: the focus is not on guaranteeing that a specific quantity of carbon remains stored in an individual building for a predefined period, but on accounting for net changes in the harvested wood product pool over time.

Several external reviews (Richter et al. 2019), including by the Swiss Federal Audit Office (EFK 2016 and EFK 2021), have raised critical issues such as that outflows were only partially and inconsistently accounted for in the first phase, which likely led to an over-issuance of certificates. As one of the timber experts that reviewed this report explained, some of these issues may since have been addressed, but as they are largely structural in nature, they are unlikely to have been resolved in full:

First, baseline determination requires assumptions about the reference-case of how much Swiss wood would have been used without the programme. The three key parameters underlying the reference scenario (EUR/CHF exchange rate, import-to-domestic production ratio, total timber volumes) have no mathematically demonstrable relationship to actual production trends, and the assumption that a stronger Swiss franc drove higher softwood imports is empirically refuted by import data from 2010–

[31] https://ssh-pbs.ch/projektumsetzung-und-monitoring/

2016, allowing the project to claim a large volume of credits even when the number of timber buildings constructed has barely changed. The reference problems are getting worse over time and are structural as modelling the reference scenario would rely on numerous parameters whose statistical significance could not be sufficiently demonstrated and would rely on industry data from 2014–2022, which is already influenced by the measures implemented due to the programme, meaning that only pre-2014 data can be used for forecasting – including for the determination of the reference scenario for 2024–2030, which is very long ago. In the first project phase, the baseline was derived through a Delphi process in which representatives of the participating firms themselves contributed to the expert estimates, a set-up the 2019 external review criticised as prone to bias, since the respondents had a direct financial interest in a conservative (i.e. low) reference development. Further, using 1990 as the reference year when determining the baseline leads to a systematic underestimation of the calculated emissions and, consequently, to an overestimation of the sink capacity. Taking into account historical emissions dating back to 1900 (as is in line with, for example, the IPCC guidelines) would be more objective and consistent with good practices. Since 2021, the baseline is instead set as a trend extrapolation of official harvest, production and trade statistics, cross-checked against WSL and KOF model results and approved as “plausible and conservative” by a three-member expert panel (WSL, KOF ETH Zurich, BFH), while still not resting on a validated forecasting model, as the 2023 validation report explicitly notes.

Second, and relatedly, additionality is not rigorously assessed (the assessment focuses on additionality of single measures like the purchase of an additional saw, not on the additionality of timber construction as such). It remains unclear whether the availability of more subsidised Swiss timber actually induces more timber construction, or simply shifts demand from imported to domestic timber.

Third, credits are currently used to offset fossil CO_2 emissions from the transport sector. This creates two problems: a potential durability mismatch as CO_2 emissions from transport have longer warming impacts compared to mitigation effects from timber storage, and a fundamental sectoral fit problem, since transport is not a hard-to-abate sector. In the long run, demand for these non-durable TCCS certificates should come from hard-to-abate sectors such as agriculture to offset short-lived methane emissions (see Venmans et a. 2025; He et al. 2026).

In parallel to this industry-level approach, private initiatives are emerging in the voluntary carbon market that focus more directly on carbon storage in buildings or portfolios of buildings. These approaches differ from the Swiss sink project in terms of system boundaries, credit ownership, monitoring requirements, permanence treatment and the level at which the carbon stock is accounted for (see Table 5). While building-level approaches can create a direct link between a specific timber building and its stored biogenic carbon, they also require robust safeguards regarding additionality, double counting, and long-term monitoring. In Switzerland, the permanence requirement is 30 years, internationally often 100 years. This means that the carbon must be sequestered in the building for 30 or 100 years in order to be counted as CO_2 storage (Frischknecht and Pfäffli 2023).

Figure 26 shows that these approaches have evolved from a forest focus to an industrial focus to a timber construction focus. This development is probably because durability, i.e. long-term storage, can be better achieved and monetised in timber construction. At an international level, forest projects have also emerged with the aim of protecting forests in developing countries, although this focus is hardly relevant for Switzerland with its regulated forests. All forest approaches – thinking in terms of forest protection – have led to a build-up of stocks and not to a sustainable use of wood that is in balance between growth and harvest, as they monetise the build-up of wood stocks in the forest and not the sustainable use of wood.



Figure 26: Development of approaches for certification and compensation of TCCS (Fedrizzi 2025).

Note: The Puro.Earth methodology "Bio-based Construction Materials" has now been discontinued, Rainbow Carbon Standard is currently certifying projects under their "Biobased Construction Materials" Methodology and EU CRCF is expected to finish their Methodology for "Carbon Storage in Products" by the end of 2026.

Internationally

Internationally, various countries and subnational jurisdictions have introduced incentive schemes for buildings that produce fewer emissions, though these schemes have generally not accounted for carbon capture or storage in biogenic materials (Pilon et al. 2024). A common regulatory approach involves mandating state agencies to consider and reduce the embodied carbon of materials used in new construction and infrastructure.

In the **United States**, several states have enacted such measures, with California and Minnesota establishing building codes that address embodied carbon through life cycle analysis (LCA). Specifically, this includes California's mandatory CAL Green Standards Code and Minnesota's B3 Guidelines, which require whole-building LCA and product Environmental Product Declarations (EPDs) for large state-funded projects. At the federal level, the Mass Timber Federal Buildings Act of 2024 proposed giving procurement priority to public buildings that use innovative wood products sourced from responsibly managed domestic forestlands (The Senate of the United States 2024).

In **Europe**, the EU Green Deal envisions a built environment aligned with circular economy principles, within which timber plays a potentially significant role. France has emerged as a forerunner in this transition through its RE2020 regulation, which took effect on 1 January 2022 and applies to new offices, residential buildings, and educational facilities. The regulation mandates analysis of embodied emissions over the full life cycle of a building and becomes progressively more stringent in 2025, 2028, and 2031. Notably, RE2020 employs a dynamic LCA approach that assigns greater weight to emissions generated earlier in a building's life, thereby favouring materials such as timber that store carbon and have low manufacturing emissions. Complementing RE2020, a sustainability law enacted the same year requires all state-funded public buildings to incorporate at least 50% wood or other bio-based materials by weight.

In Sweden, life cycle embodied carbon calculations are now a precondition for planning permission for new buildings, with binding carbon limits expected by 2027. In Finland, targets for the use of wood in public construction aim to reach 45% market share by 2025. In the Netherlands, 32 municipalities and over 80 companies and agencies in the Metropolitan Region of Amsterdam have signed a Timber Construction Covenant, committing to wood as the primary structural material in a defined share of new projects. At the supranational level, the EU will mandate measurement of embodied carbon in new buildings over 1,000 square metres by 2028, with each member state required to establish a maximum embodied carbon threshold from 2030 onwards, to be progressively tightened thereafter. In December 2025, the European Commission published a delegated regulation establishing a common methodology for calculating the life cycle global warming potential of new buildings, based on the recast Energy Performance of Buildings Directive (EPBD).

Voluntary green building certification schemes, such as LEED, BREEAM, and the DGNB system, continue to operate internationally, though they have been criticised for insufficiently recognising the carbon sequestration potential of biogenic materials, focusing instead on embodied carbon and operational lifecycle emissions (Amiri et al. 2020). At the harvesting stage, sustainable forest management standards such as the Programme for the Endorsement of Forest Certification (PEFC) and the Forest Stewardship Council (FSC) remain the primary frameworks governing responsible timber sourcing.

A critical barrier to scaling the use of wood in construction remains the absence of harmonised production standards. The diversity of non-standardised engineered wood products requires engineers and architects to calculate performance parameters for each specific supplier, significantly complicating the mainstreaming of timber – particularly for structural applications. Building codes have also historically constrained timber construction, though the 2021 and 2024 editions of the International Building Code (IBC) have expanded provisions for mass timber, introducing three new construction types (IV-A, IV-B, IV-C) and increasing allowances for exposed timber in multi-storey buildings. These reforms represent meaningful progress, though adoption remains uneven across jurisdictions, and further updates will be required to accommodate the full range of contemporary engineered wood systems.

2.3.10 Business models

In Switzerland, business models around carbon storage in harvested wood products are still in an early and largely pre-commercial stage. The handful of approaches that exist today, such as the sink project run with the Swiss Wood Sink Association and efforts by Timberfinance, are concentrated mainly around certification and ecosystem-building activities rather than around the storage technology itself. This reflects the fact that the underlying technology, the construction and processing of timber for long-term carbon storage, is already mature and widely applied; what is missing is not technical capability but a robust accounting and crediting framework that would allow this storage to be formally recognised and monetised. As a result, actors in this space are currently investing in the groundwork (standards, monitoring approaches, industry coordination) needed to eventually support a viable business model, rather than in the storage activity itself, which in small quantities already takes place regardless of whether it is credited.

TCCS providers face a unique business model challenge (Gaido 2026): The **additionality paradox** means that crediting CO_2 storage requires demonstrating that a given timber building stores carbon beyond what would have occurred without the CMA project. Because of that, regulatory promotion of timber construction could undermine the additionality on which the CDR certificate model is based. The more successfully timber construction becomes established as a regulatory standard, the smaller the certifiable surplus performance relative to the business-as-usual scenario becomes. In this case, an SRL strength could undermine the CRL of the CMA approach. This would be a pattern not accounted for in the TRL/CRL/SRL model and represents an independent conceptual extension. This paradox cannot be resolved through technological or financial support alone. From a business perspective, a mandatory disclosure requirement for realised storage performance would be a sensible first step: it creates a transparent data basis without thereby suppressing CDR incentives, and without establishing fixed quantity requirements as a standard.

The draft of the Timber in Construction Methodology by Timber Carbon under the Verra Standard tries to solve the paradox by limiting the certification depending on the regional timber construction rate per building type up to 20% or higher is already considered Common Standard; therefore, it will not be applicable for barns or single-family homes in a lot of regions. In addition, Timber Carbon's approach goes further: Regardless of the CO_2 certificate, CHF 20–30 per m^3 will be channelled into the forest on a voluntary basis, combined with requirements for sustainable forest management, so that high quality logs for construction from the forest will be available also in the future thanks to a higher log price against energy wood application. The CO_2 certificate money usually goes to the building owner, however, the flow of funds might also depend on co-benefits (Fedrizzi 2026).

Nevertheless, business models in this space will have difficulty to become stable until timber in construction removals will have reached the level of recognition like Biochar and the first compliance market for removal in long lasting products like CRCF will be in place, expecting in late 2026 (Fedrizzi 2026). Additional results from our interviews suggest that it is also important that regulators settle on a clear methodology for measuring additionality (Cafaggi 2022; Gaido 2026).

2.3.11 Main conclusion and future research

Timing: Timber Carbon Capture and Storage (TCCS) is the most mature of the carbon management approaches examined here. The technology – engineered wood in load-bearing structures – is already industrially deployed and requires neither CO_2 transport infrastructure nor geological storage sites. It can therefore be invested in today, and it is treated as a no-regret option across all DeCIRRA scenarios. What is missing is not technical capability but a robust accounting and crediting framework that allows the storage to be formally recognised and monetised.

Potential: TCCS is one of the most scalable CMAs available to Switzerland, but its potential is bounded by timber availability, by competition for biomass with other uses (e.g. pyrolysis, wood chip heating), and by the cyclicality of construction activity. Climate change is altering forest growing conditions and will progressively shift species composition, and with it the wood assortments entering the value chain. This matters directly for carbon accounting, since the available hardwood species store roughly 20 % more carbon per cubic metre than softwood (around 900 against 750 kg CO_2/m^3): a shift in species composition changes both the carbon stored per unit volume and the feedstock available for downstream capture. A disadvantage compared to established processes is that the technologies and resources required for hardwood processing involve greater effort and thus have a larger environmental footprint. Research and technological development are needed here to make these processes more efficient. The wood industry must therefore become capable of processing new species and lower-quality assortments (e.g. Scrimber), aligning long forest growth cycles with much shorter industrial investment cycles. Realising this potential requires investment along the entire forest–timber chain, particularly given the high share of imported construction timber. Future potential estimates should incorporate both productivity gains from Climate-Smart Forestry and the adverse effects of climate change on forest growth and disturbance regimes.

Costs: Recent Swiss evidence no longer supports describing timber construction as systematically more expensive than mineral construction. Cost differences are project-specific and are expected to narrow further with standardisation and prefabrication. It should also be emphasised that concrete with reduced or zero CO_2 emissions will – by whichever technology route – become increasingly expensive, which shifts the relative economics further in favour of timber.

System boundaries: More than for any other CMA examined here, results for TCCS depend on where the system boundary is drawn. Assessments that credit only biogenic storage in the building, only substitution effects, or the full forest–timber system arrive at materially different conclusions, which explains much of the apparent controversy in the literature. Defining system boundaries in a way that treats the forest and the wood product pool symmetrically over the full life cycle, while still providing a credible investment incentive, is the most important methodological research need for TCCS.

Standards/methodology: Three accounting approaches coexist: the HWP-pool approach underpinning Switzerland's regulated market ("Senke Schweizer Holz"), the object-level approach dominant in voluntary markets, and the value-chain approach proposed by Swiss Post. They are not mutually compatible: HWP-pool credits are not internationally tradable and are incompatible with the EU CRCF, which favours object-level accounting. These approaches were compared within the DeCIRRA project, and each carries distinct advantages and drawbacks (see Table 5). Further research is needed on how overlaps between compliance and voluntary market activities can be managed, so that the same biogenic carbon stock or sink service is not documented, monitored and claimed twice across different actors and accounting frameworks.

Accounting: Because countries may freely choose their HWP accounting approach under the Paris Agreement, it must be clarified where accounting gaps and where double-counting risks arise when timber is traded between countries applying different methods. At project level, the most critical unresolved issue is how the end of the building's service life is treated, since this is the point at which the biogenic carbon stored in timber products may be released. Further work is required to define how alternative end-of-life pathways should be integrated into accounting rules, and under which conditions future circularity or carbon capture solutions may be recognised without weakening the conservativeness of the approach.

Substitution effects require equally careful treatment. Avoided emissions from substituting emission-intensive materials such as concrete or steel should only be credited where they are not already accounted for elsewhere and where they are clearly separated from the accounting of biogenic carbon storage. The biogenic carbon stored in wood products in module A1 should be counted only under

removal accounting; associated fossil GHG emissions from A1–A5 may be deducted from the removal benefit, but the same reductions must not additionally be used to issue separate avoidance credits.

A further distinction is emerging in corporate GHG accounting between product-level communication and creditable carbon accounting. Under the GHG Protocol Land Sector and Removals Standard, product carbon storage is reported separately from emissions and removals and is not fungible with scope 3 emissions or removals; it requires data on product lifetime and ongoing storage monitoring plans, while requirements specific to forest product carbon storage are explicitly deferred to future versions of the standard (GHG Protocol 2026). Product suppliers may therefore communicate the carbon content of wood products, but this does not in itself constitute a monitored and creditable removal claim.

Durability/Permanence: TCCS cannot be classified as a permanent removal. Reversals may occur at the end of the building's life or earlier through fire. Permanence is achieved only where end-of-life energy recovery is equipped with CCS or where waste wood is converted to biochar through pyrolysis. Several approaches to managing the durability issue are under discussion: like-for-like replacement obligations, reversal risk management instruments such as buffer pools and insurance, and requirements to route end-of-life material to BECCS or BiCRS. Pilot projects and accompanying research are recommended to establish the practicability, costs and relative merits of these options under Swiss conditions.

Policies: Ownership of the achieved removal service must be clearly defined, particularly where compliance instruments such as “Senke Schweizer Holz” and voluntary market instruments operate side by side along the forest–wood value chain. This requires transparency of the registry and clear contractual allocation of claims between forest owners, timber suppliers, construction companies, developers, building owners and carbon project developers. Future research should therefore address how mitigation and removal benefits can be allocated between the forest owners, harvested wood products and the actors along the value chain without creating double counting.

2.4 Bioenergy with Carbon Capture (BECC)

2.4.1 General description

Bioenergy with Carbon Capture and Storage (**BECCS**) describes the CMA where biomass absorbs CO_2 from the atmosphere during growth and this biomass is used to produce energy – typically heat, electricity, or fuel –, and the resulting CO_2 emissions are captured and permanently stored. Common examples include biomass power plants or waste-to-energy facilities equipped with CCS (see Figure 27). **BioCCS** is the broader concept as it refers to capturing and storing CO_2 from any process that uses biomass, regardless of whether energy is the primary output. This includes, for example, CO_2 released during bioethanol fermentation or biogas upgrading.

BECCS and BioCCS are important CMA in carbon dioxide removal (CDR) strategies. We focus in this section on BECC and describe the transportation and storage in Section 2.6.

2.4.2 System boundaries, material and emissions flows, and main drivers

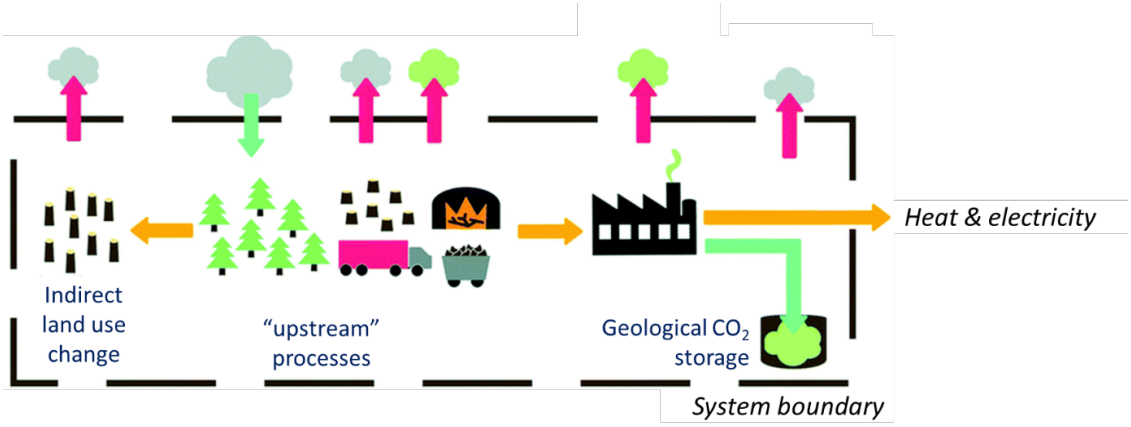


Figure 27: System boundaries of a BECCS system for heat and electricity generation.

The following processes and associated carbon fluxes must be taken into account when balancing climate impacts and have to be compared to the CO_2 emissions of natural biomass decay: The removal of CO_2 from the atmosphere during biomass growth; emissions from the harvesting and degradation of biomass; CO_2 emissions not captured at the point source; CO_2 permanently stored in geological reservoirs; GHG emissions due to land use change.

BECCS systems typically represent multi-output systems in an LCA (Fajardy & Dowell 2017; Kemper 2015; Withey et al. 2019) in which the main purpose of the biomass conversion activity determines the main or reference product and thus potentially also the functional unit. CDR as a service is one of the useful outputs of these BECCS systems and therefore associated with a positive market price (i.e., "useful product"), other output can be energy carriers, electricity, heat and/or materials. In terms of accounting for burdens (negative impacts), there are several ways for dealing with multi-functionality: First, environmental burdens of this biomass conversion activity including all previous processes in the process chain (e.g., biomass production and supply) can be partitioned and partially assigned to all useful (valuable) outputs. If CDR (e.g., the permanent removal of one unit of CO_2) represents the functional unit, other products provided by the BECCS system, for example heat and electricity generated by a biomass combustion unit with CCS, can be assigned with environmental burdens representing their relative revenue generation, proportional to production volumes and market prices (referred to as "allocation"). Second, it can be assumed that these products generated by the BECCS system replace conventional – in this case energy or feedstock – production and therefore environmental credits can be claimed, representing avoided production in a system without the BECCS system.

The type of used biomass resources or feedstock is of critical relevance for the quantification of climate impacts and environmental burdens: While the use of residual or waste biomass can be considered as free of environmental burdens in such an accounting (Antonini et al. 2020, 2021), the use of dedicated crops or biomass plantations often leads to direct and indirect land use changes associated with climate impacts, which depend on local boundary conditions (Calvin et al. 2021; Creutzig et al. 2015).

Regarding biomass conversion with carbon capture, the carbon fraction, which is captured in the biomass conversion process and permanently stored (removed from the atmosphere), as well as indirect climate impacts or other GHG emissions within the process determine the effectiveness of CDR.

In the Swiss context, the following BECCS systems seem most relevant for CDR: installations based on wood combustion, gasification or pyrolysis, waste incineration plants (sometimes referred to as Waste-to-Energy plants WtE), wastewater treatment plants (WWTP), agricultural biogas plants, and cement plants using biogenic residues for energy supply. Importantly, only the biogenic waste or energy carrier fractions used in WtE and cement plants can provide CDR, while capturing and storing CO_2 from fossil resources does not remove CO_2 from the atmosphere within relevant time scales. Thus, these biogenic carbon fractions as well as CO_2 capture rates are important for the accounting of climate impacts and the amount of CDR generated.

In case of carbon capture and sequestration (CDR), biomass combustion plants and gasifiers, WtE, WWT and biogas plants generate chemical energy carriers, chemicals/materials, or heat and electricity as co-products along with the CDR service; cement plants with CCS produce cement. Dealing with this multi-functionality applying a substitution approach seems to be the most consistent approach for accounting for the effectiveness of CDR, climate impacts and other environmental burdens, which allows for a comparison of the CDR effectiveness and overall environmental performance of BECCS systems. Such an approach would be based on the assumption that chemical energy carriers, chemicals/materials, heat, electricity and cement would replace marginal production of the fossil-based pendants, i.e. the producer with the highest production costs. This avoided production would be accounted for with environmental credits equivalent to the environmental burdens of replaced production.

Some scientific literature (e.g., Searchinger et al. 2026) argues that the use of a forest or the wood harvested from it leads to higher overall CO_2 emissions than not using it – beyond the grey energy and the consumption of fossil fuels by the machinery. While these latter two sources of CO_2 do indeed exist and can be significantly reduced through the use of renewable fuels and raw materials produced with low CO_2 emissions, the results of such assessments are usually based on a time horizon that is too short or incorrectly defined: the period under consideration ends before the forest has had time to regrow after timber harvesting, which then leads to a result that is mistakenly interpreted as an overall increase in CO_2 emissions.

In fact, it is well known that biomass grows faster in a managed forest, as the removal of trees creates a gap in the forest and stimulates growth. If no more is removed from the forest than regrows (i.e., the biomass stock remains constant in the long term), the removal thus leads to higher growth than without management. Since the CO_2 for this increased growth is removed from the air, the use of this additional wood is initially carbon-neutral or even partially negative if carbon is permanently sequestered in the form of wood, biochar, or CO_2.

Thus, if wood is not used in higher quantities than the rate of natural growth in forests (including the enhancement by harvesting), harvesting can be considered as sustainable forestry without indirect land use changes.

The comparison and evaluation of the overall impact and best use of these processes can only be done with scenario models as the increase of one process can influence the whole output and environmental burden of all other processes.

2.4.3 Co-benefits

Climate-relevant co-benefits

- Exploiting synergies with other installations saves costs and energy and therefore GHGs: larger quantities of CO_2 can be captured at one location and then processed further or prepared for onward transport. Due to the possible (heat) integration with existing plants and the much higher CO_2 concentrations, the energy input and costs are significantly lower than when capturing CO_2 from the atmosphere (point sources have 10-50% CO_2 content, atmosphere 0.04%).
- Especially for point sources with a proportion of biogenic emissions, it is possible to alternate PtX processes with negative emissions, i.e. when favourable renewable hydrogen is available, a renewable hydrocarbon is produced, while at other times the captured CO_2 is available for sequestration. In addition to this double systemic benefit (flexible energy storage, negative

emissions), there is also a certain economic advantage due to the better utilisation of the plants. The hydrocarbons can serve as (storable) energy carriers, e.g. methane, methanol, gasoline, Diesel fuel, kerosene) or as platform chemicals and intermediates (especially methanol and other alcohols/ethers). This way, they allow energy storage, sector coupling, defossilisation of hard-to-abate emissions and help to decrease energy imports and to improve the resilience of the energy system.
- If the hydrocarbons produced in PtX processes are not subsequently used in a decentralised manner – for example, as fuel – but are instead converted in a more centralised manner for energy storage (e.g., methane to electricity and heat, or methanol to hydrogen), the biogenic CO_2 used can still be captured for negative emissions.

Other co-benefits

- If other pollutants (dust, nitrogen oxides, sulphur oxides, etc.) are also captured during CO_2 capture from flue gases, this results in better air quality and less environmental pollution.
- The use of carbon capture from unavoidable sources enables the utilisation of carbon as a raw material for industry, making it more flexible and less dependent on carbon imports.

2.4.4 Risks

Climate-relevant risks

- Environmental pollution due to chemical additives (e.g., amines) and the loss of GHGs into the atmosphere (e.g., methane slip).
- Unclear allocation of negative emissions can lead to greenwashing. Transparency and control are necessary to avoid double accounting.
- The injection of CO_2 into oil reservoirs in order to increase their yield (enhanced oil recovery) can lead to the production of more fossil products and possibly keep their price low, so that more fossil fuels are consumed overall.
- The high energy requirements of carbon capture can lead to energy price increases. It may be possible that the energy used will then be lacking in other important areas, the overall system efficiency might decrease and gaps in the supply of thermal and electrical energy might arise.
- Political promotion of certain technologies, e.g., enforced capture only in certain processes, can lead to distortions and prevent the best or most efficient solution from an overall system perspective.

Other risks

- Depending on the procedure, the operating licence and insurance requirements are unclear.
- Safety of CO_2 storage sites and of the buildings/infrastructure close to it.
- Strict environmental regulations and high energy prices can lead to the relocation of industries if conditions for producers abroad are perceived as more attractive. Industrial subsidies, energy price caps, or, for example, the Carbon Border Adjustment Mechanism (CBAM) can influence the assessment of boundary conditions.

2.4.5 Accounting

GHG inventory accounting

The IPCC Guidelines for national inventories provide clear guidance on accounting for capture and (underground) storage of CO_2 from point sources. This guidance applies to all activities which involve underground storage of CO_2 (CCS) regardless of whether the carbon is biogenic or not: in the GHG inventory sector in which CO_2 was captured, the volume of CO_2 captured in any given year is subtracted. The stored CO_2 is recorded as a memo item in the energy sector of the storing country without affecting its total emissions figure. Ambiguity remains in cases of international transfer of CO_2 for CO_2 capture: In one interpretation, the resulting CO_2 removal should be counted in the inventory of the capturing country (while the storing country only makes the notation of storage in the energy sector). According to a second interpretation, however, the storing country would first account for the storage (which it could then sell to the capturing country as an ITMO). Any CO_2 leakage during transport or storage is declared in the energy sector of the country in which the leakage physically occurs (Eggelston et al. 2006, Chapter 5, Section 5.10).

The IPCC Task Force on National Greenhouse Gas Inventories has been mandated to deliver a methodology report on carbon dioxide removal, CCS and CCU by the end of 2027, which is expected to clarify how removals, including from BECCS, should be reported under the UNFCCC (Edwards et al. 2026).

Baseline- and monitoring reporting and verification

On the crediting side, both the American Carbon Registry and Verra's Verified Carbon Standard have developed MRV methodologies that allow crediting of reductions or removals from CCS/BECCS activities for sale on the voluntary carbon market. Puro.earth integrated the CCS+ initiative's BECCS (and DACCS) methodology framework into its own certification and issuance framework in October 2025 (Puro.earth 2025).

Under the Paris Agreement, the Article 6.4 Supervisory Body adopted standards on activities involving removals (October 2024, endorsed at COP29), so BECCS activities are in principle eligible under the PACM once activity-specific methodologies are approved. At EU level the CRCF now provides a certification route for BioCCS removals (see Section 2.4.9 below), which could in future be linked to compliance instruments.

Standardisation of quantification is also progressing: in July 2025 the British Standards Institution published a dedicated specification for BECCS (BSI 2025a).

2.4.6 Estimates of costs, potentials, and main drivers

The costs of carbon capture from various industrial processes were analysed in a study by the IEA (IEA 2022) and are shown in Figures 28 and 29. As expected, the lower the CO_2 concentration, the higher the capture costs for CO_2. Accordingly, direct air capture is the most expensive (0.04% CO_2 in the air), followed by flue gases due to their high proportion of nitrogen and residual oxygen, and the waste gases from cement production. Processes in which CO_2 is produced as an important co-product, e.g. gasification, anaerobic digestion or alcoholic fermentation, therefore have the lowest CO_2 supply costs. In these facilities, CO_2 has so far been a byproduct, so the only costs incurred initially are compression costs of US$15–25 per ton. However, since the volumes are small, the price is likely to align with that of the next most expensive biogenic source – namely, CO_2 from municipal solid waste incinerators – as soon as demand warrants it. As shown in the paper by Becattini et al. (2022), the transport costs of CO_2 to a storage site in the North Sea range from US$100 to US$150/t, depending on the development of transport logistics, while the actual storage costs are lower than this cost uncertainty. This results in Figure 30 below, which shows the costs for BECCS. Not included are the positive contributions to the overall energy system enabled by the flexible use of biogenic CO_2 for PtX applications in the summer as seasonal energy storage.

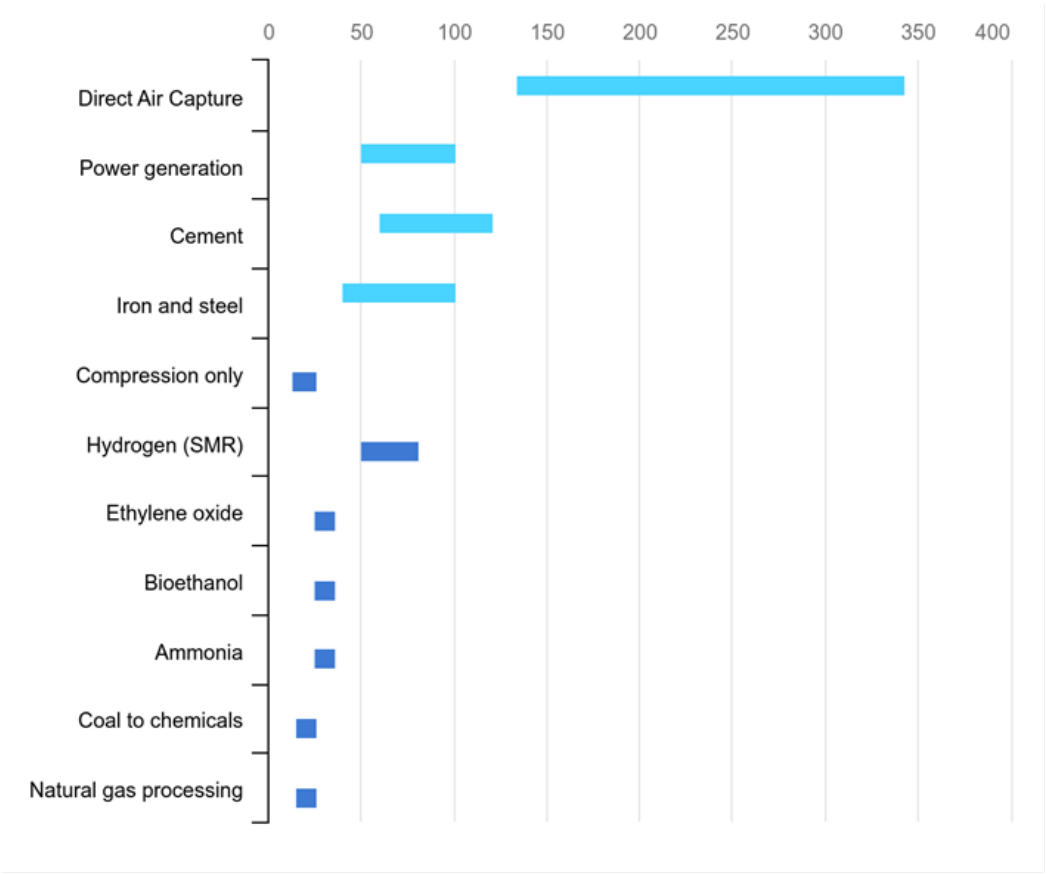


Figure 28: Costs (in US$/t$CO_2$) of only the carbon capture from different industrial processes (IEA 2020).

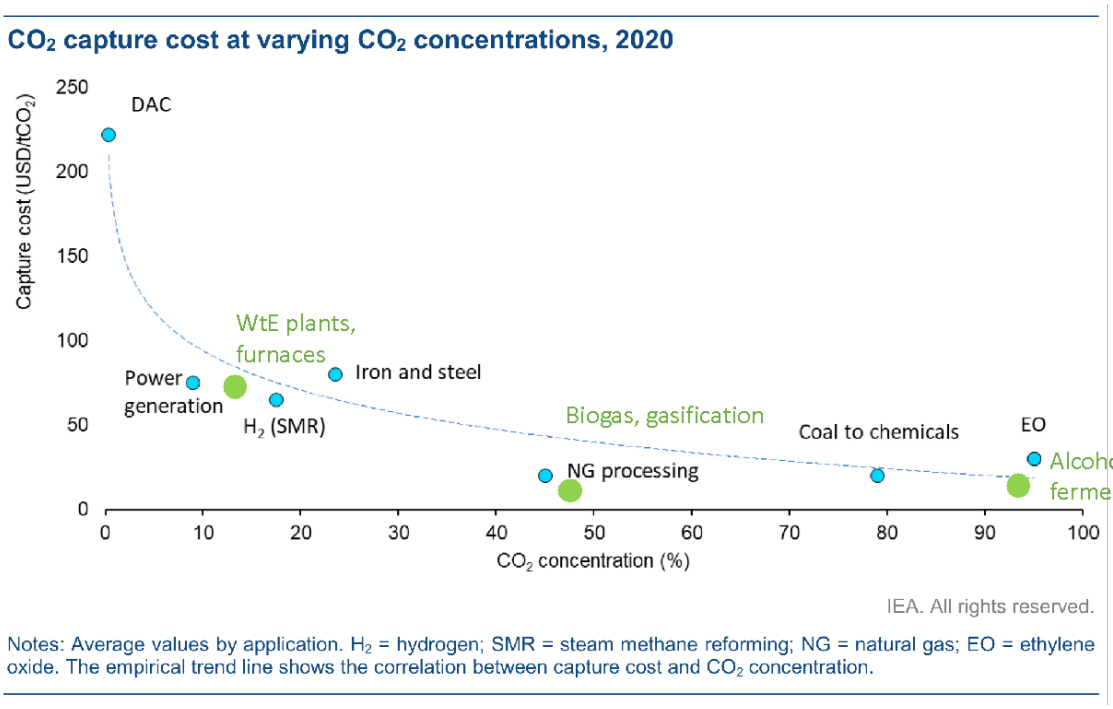


Figure 29: Costs of only the carbon capture from various industrial processes (IEA 2022, p. 27). Biomass-based processes were added by the authors.

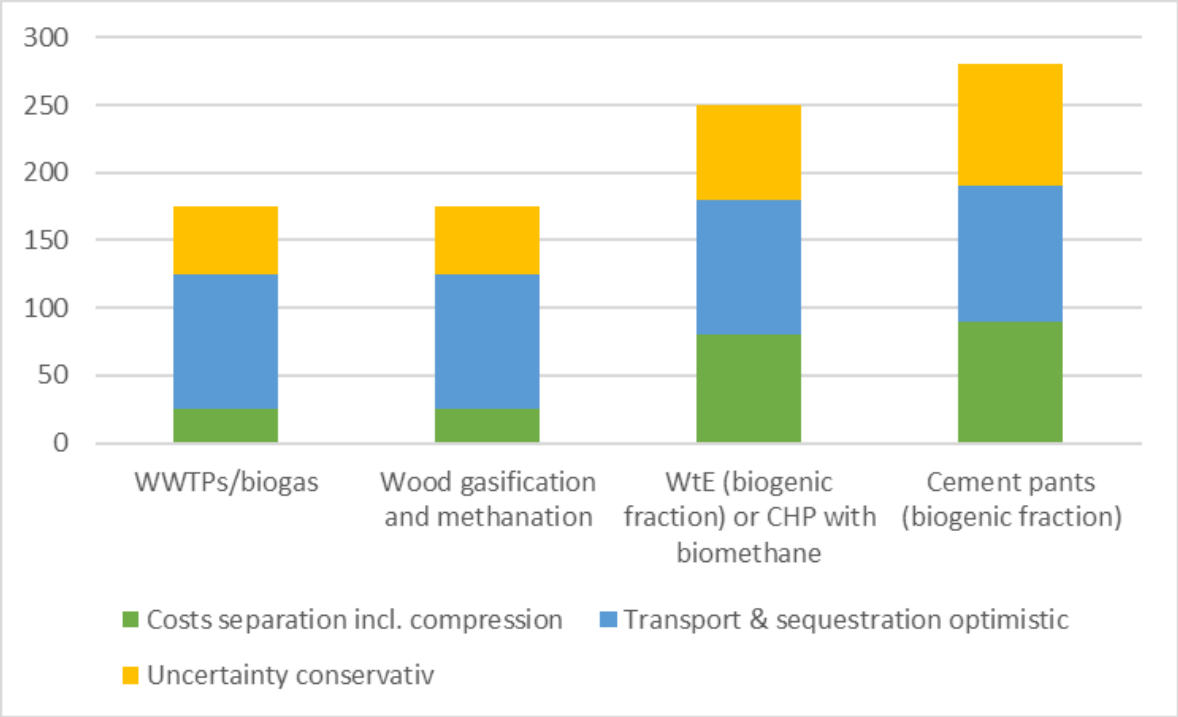


Figure 30: Costs estimation (€/tCO_2) of BECCS, i.e., including transport and final sequestration (based on Becattini et al. 2022).

Typical CO_2 contents of gases from industrial processes used in Switzerland are listed in Table 6. The other components such as oxygen or methane content have an influence on which capture technologies can be used.

Table 6: Typical CO_2 contents of gases from industrial processes used in Switzerland.

CO_2 sources	**Cement plant**	**WtE / Furnaces**	**Biogas / Wastewater treatment plant**	**Gasification / Synthesis**
CO_2 content	>15%	<12%	37-50%	30-50%
O_2 content	>10%	>9%	< 1%	0%
Methane content	0%	0%	62-50%	0-45%

Processes for the separation of CO_2

Table 7 lists processes for the separation of CO_2 from industrial gas mixtures. Examples of these processes in Switzerland are also given. Scrubbers in which CO_2-containing gas is brought into contact with scrubbing agents, usually in counter current (see Figure 31), are very widespread. Possible modes of action here are physical adsorption, in which the CO_2 is bound due to its higher relative solubility, or chemical scrubbers. In the latter case, a reversible chemical bond is formed. A chemical bond has the advantage of higher selectivity and capacity of the scrubbing agent (at low partial pressures) but requires a higher energy input (usually higher temperatures >160°C) for the regeneration of the scrubbing agent.

The situation is similar with the adsorption of CO_2 on solids. In the widespread pressure swing adsorption (PSA), the CO_2 is adsorbed preferentially at higher pressures on a suitable solid sorbent (e.g., molecular sieves). As this is a physical effect, reducing the pressure is sufficient to regenerate the sorbent. Since, unlike with continuous scrubbers, this is a transient process, in reality four vessels in the different phases of adsorption and regeneration are usually applied in order to achieve continuous CO_2 separation.

Table 7: Processes for separating CO_2 from gas mixtures.

Absorption (in liquids)	**Membranes**	**Adsorption (on solids)**	**Cryogenic**
Physical: ● Pressurised water scrubbing at biogas plants ● Rectisol (MeOH, coal gasification)	Polymer membranes, e.g. WWTPs of Brugg, Turgi, Reinach, Wildegg	Physical: ● Pressure swing adsorption (PSA)	Liquefaction of CO_2 (e.g. at the Bachenbülach biogas plant)
Chemical organic: ● Amine scrubbing (e.g. SFPI biogas plant, Werdhölzli WWTP, Norcem Breivik)		Chemical: ● Pressure/temperature swing adsorption ● Calcite/carbonate (e.g. sorption enhanced gasification)	
Chemical inorganic: ● Potassium hydroxide (KOH) ● Potassium carbonate (K_2CO_3/$KHCO_3$) ● Chilled ammonia (e.g. cement factory in Norway)			

While cryogenic separation processes are based on the different boiling points of the gases, polymer membranes (e.g. polyimides) utilise the easier permeation of CO_2 – compared to methane or nitrogen – for biogas treatment. For this reason, a pressure difference of between 10 and 20 bar is usually sufficient to treat biogas in two or three stages. However, due to the even higher permeation of hydrogen, these membranes are not suitable for separating hydrogen-free CO_2 from synthesis gases.

Scrubbers are mainly used in larger plants, as they are comparatively expensive on a small scale and become significantly cheaper when scaled up. For small plants, especially biogas plants, pressure swing adsorption, membranes and, more recently, cryogenic separation are more commonly used. The choice of CO_2 separation process must be made specifically for each site, as the cost differences between the processes may be smaller than synergies in (energy) integration with existing processes or existing infrastructure, depending on the situation.

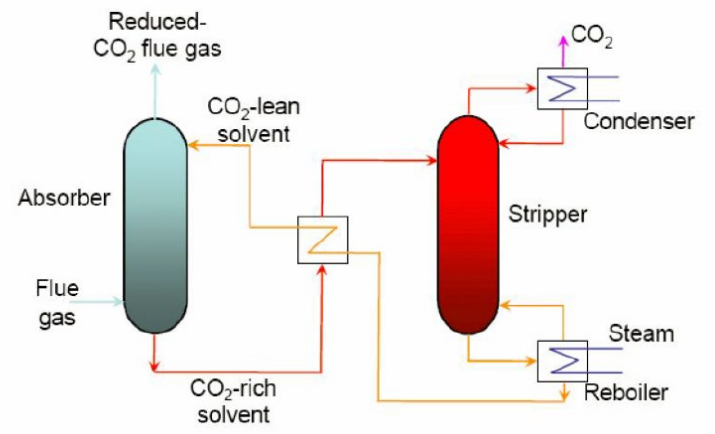


Figure 31: Schematic sketch of a CO_2 scrubber (e.g., amine scrubber).

Potential point sources in Switzerland

A study by Empa and PSI (Teske et al. 2019) determined the potential for Power-to-Gas in Switzerland and also presented the CO_2 point sources (see Figure 32), focussing on cement plants, waste incineration plants (WIPs) and wastewater treatment plants (WWTPs). The six cement plants each represent the largest point sources, but all WIPs together emit more CO_2 than all cement plants, which is why WIPs are particularly relevant for decarbonisation. The CO_2 from WWTPs is almost 100% of

biogenic origin and is therefore suitable for negative emissions. However, it only accounts for a very small fraction of total emissions and there are more than 500 such plants, which would make it very costly to utilise the potential. In contrast, the biogenic share of WIPs is around 50% (Verband der Betreiber Schweizerischer Abfallverwertungsanlagen (VBSA) 2023) and just under 10% for cement plants (Nakhle et al. 2022, Figure 5). The greatest potential for biogenic CO_2 and thus negative emissions is therefore to be found in waste incineration plants.

As all point sources have the potential to convert CO_2 into other products as part of CCU, e.g. in PtX applications, there is a certain amount of competition with CCS or negative emissions. However, as electricity is likely to be scarce and expensive at certain times (winter) in the future, a certain seasonal flexibility is necessary (Moioli & Schildhauer 2022), so that the CO_2 is used for energy-intensive PtX applications when electricity prices are low, but for CCS or, in the case of biogenic CO_2, for negative emissions when prices are high. Accordingly, the (BE)CCS potential at such a point source could fall by a factor of around two. However, if the CO_2 may be captured again when the products from the PtX are utilised, the potential increases again.

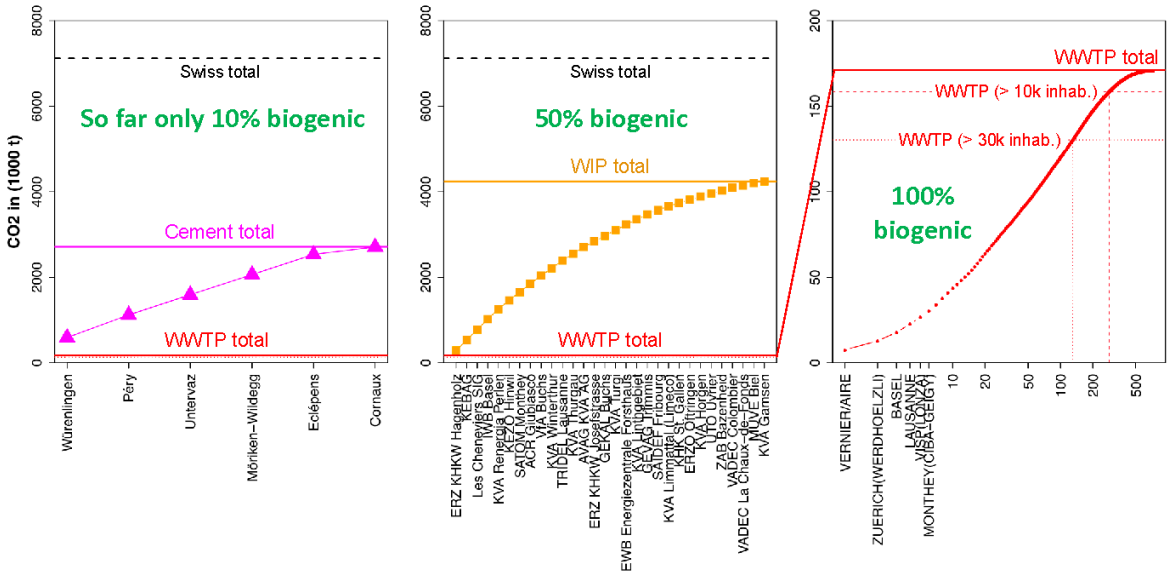


Figure 32: CO_2 point sources in Switzerland: cement plants, waste incineration plants (WIP) and wastewater treatment plants (WWTP); cumulative presentation of annual CO_2 emissions, sorted by decreasing contribution of the plants in each (Teske et al. 2019).

Note: The graph on the left shows the emissions of the individual cement plants (pink triangles and the cumulative value (pink line); the WWTP cumulative red line is shown below for comparison. In the centre are all the individual waste incineration plants (small squares) and the cumulative quantity as a yellow line. In comparison again WWTP. The graph on the right shows only the emissions from WWTP. The comparison to the first two graphs shows that WWTP emissions are very small compared to those from the other sources.

For the Swiss cement industry as the largest emitter, the various levers, potentials and costs were listed in detail in an ETH study (Nakhle et al. 2022). These are, in particular, alternative and biogenic fuels as substitutes for fossil fuels in clinker production. The higher the proportion of biogenic fuels in the cement plant, the more BECCS can be operated. However, the proportion is limited to a maximum of 30% of the CO_2 emissions, as the remainder comes from geogenic emissions from calcination.

In addition, clinker substitution in cement is of particular importance, which has been driven forward for over 30 years and has already allowed significant reductions in CO_2 emissions per tonne of cement, see Figure 33.

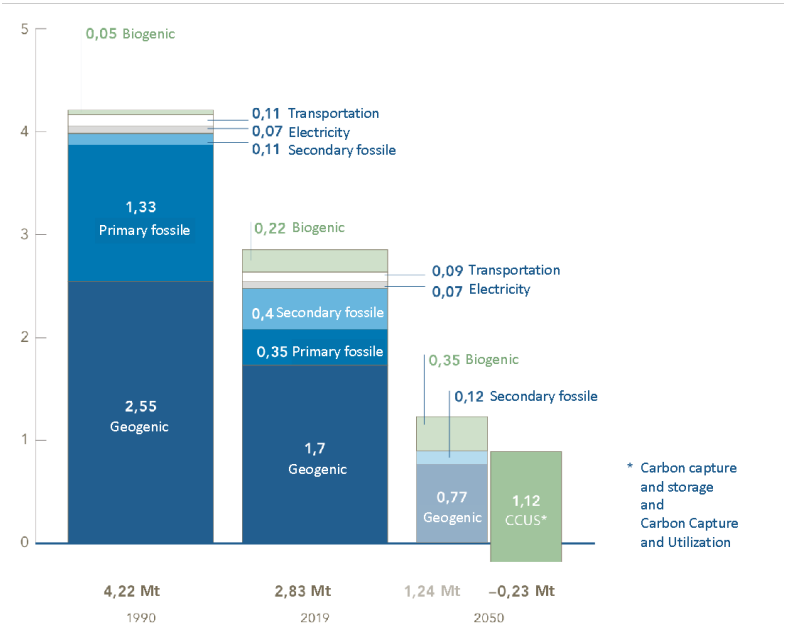


Figure 33: Emissions from the Swiss cement industry in 1990, 2019 und 2050 (Cemsuisse 2021).

Quantitative potential for BECCS in Switzerland

At existing larger WWTPs (>30000 Einwohnerwerte) close to the gas grid
Biogenic CO_2 in total: ca. 120 kt/year
Biogenic CO_2 when using half for PtX (seasonal flexibility): ca. 60 kt/year
Biogenic CO_2 with CC in case centrally using all energy carriers from PtX (biomethane plus PtG-based methane, e.g. in combined cycles during winter): 160 – 250 kt/year, but as expensive as CO_2 from incineration plants
There is a similarly large potential from manure and agricultural biogas plants, but with more challenging logistics

Potential future biomass gasification with methanation
Energy in unused sustainable wood potential according to WSL study (Thees et al. 2017): 14 PJ/year
Biogenic CO_2 from process inherent CO_2 separation: max. 600 kt/year
Biogenic CO_2 when using half for PtX (seasonal flexibility): ca. 300 kt/year
Biogenic CO_2 with CC in case centrally using all energy carriers from PtX (biomethan plus PtG-based methane, e.g. in combined cycles during winter): 600 – 1000 kt/year, but as expensive as CO_2 from waste incineration plants
There are a few 100 kt/year more of biogenic CO_2 in exhaust gas of thermal power plants using biomass, but as expensive as CO_2 from waste incineration plants

Existing waste incineration plants (WIP, WtE, KVAs) with 50% biogenic fraction
Biogenic CO_2 in total: ca. 2000 kt/year
Biogenic CO_2 when using half for PtX (seasonal flexibility): ca. 1000 kt/year
Biogenic CO_2 with CC in case centrally using all energy carriers from PtX: 1000 – 2000 kt/year

Existing cement plants with 10% biogenic fraction
Biogenic CO_2 in total: ca. 250 kt/year
Biogenic CO_2 when using half for PtX (seasonal flexibility): ca. 120 kt/year
Biogenic CO_2 with CC in case centrally using all energy carriers from PtX: 120 – 250 kt/year

2.4.7 The role of BECC across scenarios

In all four DeCIRRA scenarios, CO_2 (both biogenic and fossil) is captured both at large point sources and from biogas plants, but the volume captured at large point sources differs significantly between scenarios (see Figure 34). Only the Clam and Butterfly scenarios capture substantial quantities from

large point sources – namely waste incineration (KVA) and cement plants, therefore not all of it is biogenic. This may be due to the fact that both scenarios do not allow the use of international offsets, requiring more capture domestically. In the Octopus scenario, captured CO_2 originates mainly from chemical processes and biogas plants – 100% biogenic – rather than from these large point sources. In the Snail scenario, with high transport costs and the use of international offsets, total captured volumes remain comparatively low, at around 1.3 Mt CO_2.

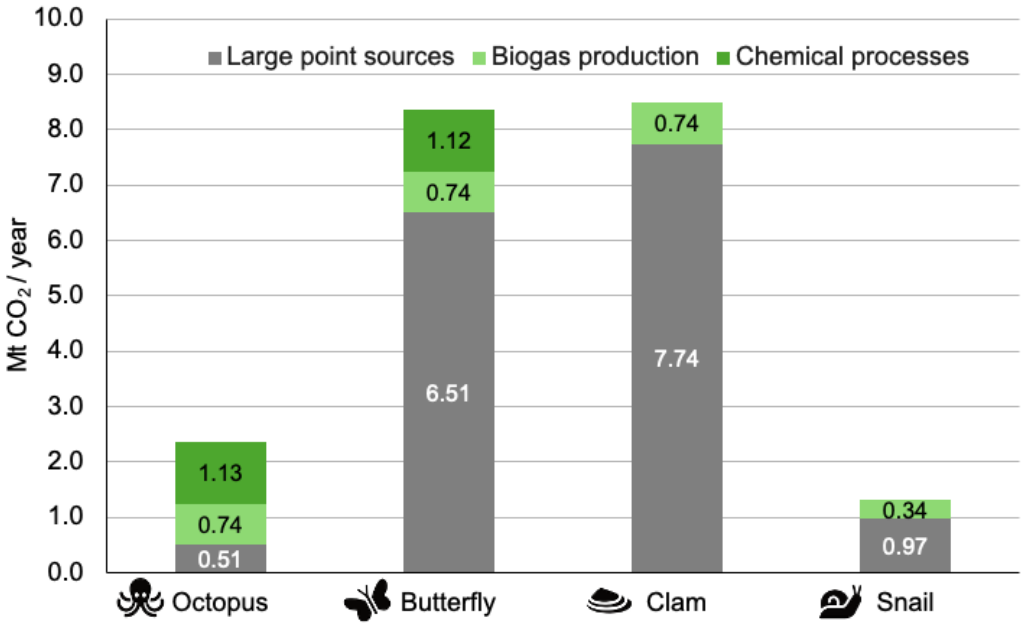


Figure 34: CO_2 capture from point sources within Switzerland in the DeCIRRA scenarios (Mt CO_2/year).

2.4.8 Relevant actors and projects

The majority of Swiss NET actors are involved in (BE)CC, including CO_2 emitters, providers of storage solutions, service providers and regulators, as our survey of NET actors showed (Dittli 2023). The following actors are particularly important for BECC:

Regulators
FOEN and SFOE: These two federal offices play a coordinating role and decide on project funding. They are mentioned most frequently in the survey. The SFOE must ensure energy security, as the capture of CO_2 from electricity-generating point sources has an impact on electricity production and is therefore heavily involved in various projects.

Emitters
In third place are the waste incineration plants, which play a very important role in the context of BECC, as both biogenic and fossil waste are incinerated in WIPs. Various projects to reduce emissions are currently being driven forward in Switzerland. For example, the Linth waste incineration plant is planning a pilot CO_2 capture project[32] together with the ETH and the VBSA[33], as the two furnaces will have to be replaced as part of an overall modernisation in 2025.

The large cement plants, such as Holcim, Jura Cem and Vigier, are also frequently mentioned, as biomass is also used in cement production. These are usually represented externally by the Cemsuisse association[34], one of the DeCIRRA implementation partners and actively involved in the decarbonisation debate.

[32] https://www.kva-linth.ch/energie-umwelt#section-id-100
[33] https://vbsa.ch/
[34] https://www.cemsuisse.ch/

Wastewater treatment plants (WWTPs) are also important emitters and therefore potential capture sites, even if the total amount of carbon is lower and it would be rather costly to equip each individual plant with CCS due to the high number of plants.

Wood is also used to generate heat and/or electricity in numerous smaller and larger combined heat and power plants throughout Switzerland. These are also important players for potential capture.

Other emitters are the chemical and other industries, which were mentioned less frequently in the survey.

Other private actors
Many plant construction companies offer capture systems.

Organisations and companies that operate marketplaces or develop and finance NET projects are important for implementing projects and ensuring the flow of funds. This also requires close co-operation with the financial industry.

Airfix and Southpole are involved in planning the first CO_2 capture projects at WIPs.

Research
Research institutes such as ETHZ, EPFL and ZHAW are very active and are investigating, for example, better materials for CO_2 capture or the acceptance of such measures. They are involved in various research projects that deal with BECC.

Empa and PSI are studying new materials and processes in connection with the capture of CO_2 and its utilisation – together with hydrogen – for the production of gases.

Associations and foundations
Swiss Climate Foundation supports projects to reduce GHG emissions and promote sustainable technologies.

As mentioned above, the two most important associations are CemSuisse and the VBSA. However, Holzenergie Schweiz (Swiss Wood Energy)[35] must also play an important role in the future, as wood plays a central role in wood-fired power plants and other processes.

The Risk Dialogue Foundation[36] operates the Swiss Carbon Removal Platform[37], informs and brings together the industry, and organises events and meetings on a regular basis. It is also involved in many projects, including DeCIRRA.

2.4.9 National and international policies and incentives

To assess the policy framework for BECCS, different frameworks need to be considered depending on the different contexts in which BECCS can be applied, including cement plants, waste incineration and wastewater treatment plants.

In Switzerland

Policy support for BECCS technologies is only starting to be adopted in Switzerland. First measures include (i) making CCS projects eligible as compensation projects under the CO_2 Ordinance, (ii) the dedicated funding of around 50 million CHF from the Climate Cent Foundation for NET and CCUS projects, (iii) the agreement between the Swiss government and the Swiss association of waste-to-energy plant operators (VBSA) (FOEN 2023), as well as (iv) financial support under the Climate and Innovation Act (KIG) and the CO_2 Act.

From 2022, **attestations for negative emissions** achieved nationally or internationally can be issued if they meet the requirements under Art. 5 and Annex 19 of the **CO_2 Ordinance**. Such attestations can be used by installations with a reduction obligation under the CO_2 Act toward meeting their commitments. They can also be used by fuel importers to meet their emissions compensation obligation (FOEN 2025a).

[35] https://www.holzenergie.ch/
[36] https://www.risiko-dialog.ch/
[37] https://www.carbon-removal.ch/

The **Climate Cent Foundation** focuses its remaining resources, until 2032, primarily on private-sector projects that durably remove hard-to-avoid CO_2 emissions (NET) or capture and store CO_2 at the point of production (CCS). Following a 2022 call for proposals, five projects received funding approval in February 2023, all involving CO_2 capture in Switzerland, mostly at biogas facilities, with three storing the CO_2 in building materials domestically (ReCO2ver/Sika; zirkulit; BEST/Neustark) and two exporting it for permanent underground storage abroad (CO_2 Energie, Nesselnbach; TOGETHER/Neustark). Funding agreements for an overall CHF 50 million were signed in August 2023; as of August 2025 the expected funding totaled about CHF 45 million (Climate Cent Foundation 2025).

Under the **agreement between the VBSA and the government** (FOEN 2023), the waste-to-energy operators have committed to putting in operation at least one CCS plant with a capacity of at least 100,000 tCO_2 per year until 2030. To ensure that this goal is achieved, several qualitative milestones have been agreed, with specific timelines for, e.g., estimating the potential for CCS in all waste-to-energy plants, establishing the location for the project, finalising the construction project, etc. If the goal is nonetheless not achieved, the waste-to-energy plants will have to participate in the Swiss ETS.[38]

The most advanced waste-to-energy CCS initiative in Switzerland is at KVA Linth in Niederurnen (Canton Glarus), which the Swiss waste-to-energy operators selected as the site for the first plant to be realised under the VBSA branch agreement. Together with the VBSA and ETH Zurich, and with support from Innosuisse and several cantons (Glarus, Schwyz, St. Gallen and Zurich), KVA Linth investigated capture at its site during the "KVA Linth 2025" plant-renewal programme, with the captured CO_2 to be transported and stored abroad. A pre-project found that two post-combustion capture methods (amine scrubbing and high-pressure capture) could both be integrated into the plant, with investment costs of roughly CHF 160–175 million and levelized capture costs of about CHF 340–390 per tonne of CO_2, and judged export and storage of volumes on the order of 100 kt CO_2/year from 2030 onward to be realistic (Marxer et al. 2026). However, financing for commissioning by 2030 could not be secured in time: the envisaged mechanism – a solidarity levy on waste incineration across all Swiss plants – lacks a legal basis, and the VBSA–UVEK branch agreement covers construction but not operation. The report also notes that CO_2 captured for storage is legally classified as waste in Switzerland (requiring a FOEN export permit), and that the key legal foundations for national CO_2 logistics infrastructure and its financing are being developed in the forthcoming CCS framework legislation, due to enter consultation in 2026 (Marxer et al. 2026).

The **KIG** entered into force on 1 January 2025. Its Article 6 makes available CHF 1.2 billion over six years (up to CHF 200 million per year until 2030) to support companies that deploy innovative climate-friendly technologies, including CCUS and BECCS, in implementing their net-zero roadmaps. The conditions for accessing this funding are set out in the Climate Protection Ordinance (KIV), also in force since 1 January 2025: applicants must draw up a net-zero decarbonisation roadmap identifying the measures to be funded, including both a reduction pathway for emissions and a development pathway for negative emissions to balance the company's remaining emissions. The funding is administered through the programme ITINERO, run jointly by FOEN and SFOE; applications can be submitted on a rolling basis since 1 July 2025, and CCS/CDR measures are handled through a two-stage thematic call procedure owing to their complexity (ITINERO 2026; FOEN 2025a).

The first funding decisions under ITINERO were announced in March 2026. In the first thematic call on CO_2 removal and storage, 21 pre-proposals resulted in three full proposals submitted, with one receiving a positive funding decision: a BECCS project led by Regionalwerke Baden AG which will capture CO_2 at the Otelfingen biomass power plant, transporting part of it to a European site for permanent geological storage and using the remainder as a climate-neutral industrial gas to replace fossil CO_2 sources; the capture technology is being deployed for the first time in Switzerland (ITINERO 2026). This is the first Swiss BECCS project to secure public funding under the KIG.

Under the CO_2 Act (Art. 37b), operators of installations participating in the ETS can apply for investment support for decarbonisation measures including CCS and NET. The funding is obtained from part of the proceeds of the auctioning of emission allowances for the installations ETS (FOEN 2025a).

BECCS in cement plants are currently covered under the Swiss ETS which so far does not include the possibility to issue removal units. Nonetheless, emissions from point sources covered by the ETS that are captured and stored permanently in geological formations or in building materials in Switzerland or

[38] However, if the operation of the plant is delayed due to regulatory delays of opposition from affected third parties, the deadline can be extended for up to two years.

in countries with a bilateral agreement with Switzerland are not considered relevant for ETS purposes (CO_2 Ordinance, Art. 55 para. 1bis; see also further discussion on BECCS and ETS below). Wood energy plants are exempted from the Swiss ETS.

More broadly, the Federal Council frames the expansion of CCS and NETs as a two-stage process: a pioneering phase to 2030 and a scaling-up phase to 2050. It estimates that around 12 Mt CO_2/year will need to be captured and stored via CCS and NETs by 2050 (about 30% of current Swiss emissions), with interim steps of 500,000 tonnes by 2030 and 1.2 Mt by 2035. The revised CO_2 Act and the KIG are considered adequate for the pioneering phase, but no legal framework yet exists for the post-2030 scaling-up phase; the Federal Council is expected to open a consultation on the post-2030 rules by the second quarter of 2026, and Parliament has instructed the government (Motion 24.4256) to develop a national regulatory framework for the capture, transport and storage of CO_2 (FOEN 2025a).

Internationally

Filtering the IEA Policies database for measures tagged with CO_2 capture, CO_2 storage or direct air capture technologies returns about 165–170 policies, the majority in force, concentrated in the United States, the United Kingdom, Australia, Japan, Canada, the EU and the Nordic countries (IEA 2026a). Notable standing programmes include Canada's Investment Tax Credit for CCUS, the EU's Net-Zero Industry Act provisions on CO_2 injection capacity, the United Kingdom's suite of CCUS instruments (the CCS Infrastructure Fund, the CCUS Investor Roadmap and CCUS Innovation programmes, including a Hydrogen BECCS Innovation Programme), and Japan's CCS Long-Term Roadmap and Green Innovation Fund streams for CO_2 capture and recycling.

In the US, the Section 45Q tax credit established fixed amounts per tonne of CO_2 permanently stored, with higher rates for direct air capture and storage (DACS) than for other CCUS technologies. Under the "One Big Beautiful Bill Act" of July 2025, the tax credit was maintained at US$ 85/tCO_2 for point-source capture and US$ 180/tCO_2 for direct air capture with dedicated geological storage. Parity was created so that CO_2 used in products or in enhanced oil recovery now qualifies for the same credit value as CO_2 that is permanently stored (Min 2025).

Sweden has operationalized its reverse-auction scheme to specifically support investments in BioCCS. In April 2024 the European Commission approved Sweden's roughly SEK 36 billion (≈ EUR 3 billion) state-aid scheme to support permanent removal of biogenic CO_2 through BECCS, and the Swedish Energy Agency opened the first reverse auction in August 2024. In early 2025 it awarded the first contract to Stockholm Exergi: support of just over SEK 20 billion (≈ EUR 1.7 billion), disbursed over a maximum of 15 years from the start of geological storage, for the permanent capture and storage of more than 11 Mt of biogenic CO_2 (Swedish Energy Agency 2025). This is one of the largest single BECCS support commitments to date.

Denmark has likewise moved from planning to award. Its Negative Emissions Carbon Capture and Storage (NECCS) fund, endowed with about DKK 2.5 billion and dedicated specifically to biogenic CO_2 sources, completed its first tender in April 2024, selecting three projects expected to capture around 160,000 tonnes of biogenic CO_2 per year between 2026 and 2032 (Danish Energy Agency 2024). This complements Denmark's larger CCS/CCUS fund, under which Ørsted was awarded a 20-year contract in 2023 (around EUR 1.1 billion) to capture and store about 0.4 Mt biogenic CO_2 per year from its Asnæs and Avedøre plants from around 2025-2026 onward (Ørsted 2023).

Other support measures in OECD countries include operating subsidies for CCUS projects, which provide support per tonne of CO_2 captured and have been introduced in Australia (CCS Hubs and Technologies programme) and the Netherlands (SDE++ Subsidy Fund), as well as tax credits for CCUS investments in Canada. The Canadian tax credits are established on a percentage basis, with the rates decreasing after 2031 to encourage rapid adoption, and with Enhanced Oil Recovery projects considered not eligible.

BECCS installations currently do not fall within the scope of the EU ETS. The underlying difficulty is structural: to reach net zero, the supply of emissions allowances will need to approach zero or turn negative before 2050, which is hard to reconcile with a cap-and-trade system premised on installations that generate emissions for which allowances must be surrendered. The current ETS Directive incentivises CCS by providing that allowances need not be surrendered for emissions captured and transferred to an authorized storage site (Article 12(3a)), but this incentive is limited to fossil-based installations, so the ETS does not yet provide a legal basis for generating CO_2 removal credits (Rickels et al. 2020). Proposed ways of amending the ETS to incorporate removals include (i) integrating them

subject to quantity and sectoral limitations to avoid diluting the incentive for actual emission reductions (analogous to the Kyoto Protocol's flexible mechanisms); (ii) imposing obligations to use a minimum quantity of removal credits while removals remain uncompetitive; or (iii) admitting biomass-burning installations into the ETS while managing the LULUCF double-counting risk, e.g. by allocating free allowances that installations can sell once they have captured and stored their biogenic CO_2 (Rickels et al. 2020).

The EU is now moving from debating this question toward concrete action. With the CRCF Regulation in force and the first delegated regulation certifying methodologies for permanent removals – including bioenergy carbon capture and storage (BioCCS) – adopted in February 2026, the EU now has a certification infrastructure that could feed removal units into compliance markets. The Commission is required to assess the possible inclusion of permanently stored, CRCF-certified removals in the EU ETS. The Parliament–Council agreement on the EU 2040 climate target (from late 2025) explicitly identifies the ETS revision as the vehicle for building a business case for domestic permanent removals (Council of the EU 2025; Jensen 2026).

Indeed, in its July 2026 EU ETS revision proposal (Art. 9c),[39] the Commission proposes a limited integration of carbon removals into the EU ETS, for the first time introducing a predictable demand for removals in compliance markets. Only domestic permanent CRCF-certified removals (BioCCS and DACCS) will be eligible, and safeguards will be introduced to preserve environmental integrity and maintain incentives to reduce emissions rather than compensating them. Specifically, the proposal envisages an increase in the EU ETS cap by 250 million allowances, which will be made available to the Commission for purchasing an equivalent quantity of BioCCS and DACCS removal units over the period 2031-2040, ensuring that the Commission itself has the control over what quality of removals enters the market. In addition, operators would be allowed to use CRCF-certified BioCCS removals that they themselves generate to compensate their own fossil emissions (Art. 14(1a)), which would however count toward the overall cap increase of 250 Mt CO_2e. In addition, the Commission EU ETS proposal (Art. 12a) envisages a gradual phase-in of waste incineration and waste co-incineration installations into the EU ETS starting from 2031, with 25% of their verified emissions subject to surrendering allowances in the year 2031, 50% in 2032, 75% in 2033 and 100% from 2034 onward (see also Lopez Hernandez 2026; Warringa & Manna 2025). This is relevant for waste-to-energy BECCS and the Swiss VBSA arrangement under which waste-to-energy plants face ETS participation if the VBSA CCS milestone is missed.

According to CDR.fyi (2026), BECCS accounts for the large majority of contracted durable carbon-removal volume, but comparatively few units (about 79,000 tonnes) have been physically delivered to date, as most large facilities are still pre-operational (see Section 3.4).

2.4.10 Business models

BECCS operators target industrial and energy sector clients, offering energy (electricity, heat and methane) alongside negative emission certificates. Because BECCS is currently not financially viable without subsidies or a high CO_2 price, the business model logic depends critically on regulatory support, government subsidies or long-term offtake agreements. The cost structure of BECCS is determined by the capital expenditure for CO_2 capture, transport, and storage, as well as by biomass supply (Ishaq & Crawford 2025). The literature reports varying costs depending on plant type, ranging between 100 and 400 US$/t$CO_2$, with an expected cost reduction to around 150 €/tCO_2 by 2050 (Abegg et al. 2024; Cames et al. 2023). Currently, BECCS removals are traded at approximately 220 US$/t$CO_2$ (CDR.fyi 2026). In one interview an expert of small agricultural biogas plants described potential production cost of about 550-600 CHF/t incl. transport and storage abroad (Gaido 2026).

Gaido (2026) describes in his thesis that for all CCS the dominant barriers are infrastructural, thereby confirming the infrastructure requirements for CCS-based technologies described in the literature. The chicken-and-egg problem of CO_2 transport infrastructure is independently identified by several stakeholders as the most critical bottleneck: no investor will build a network without guaranteed utilisation, and no utilisation is possible without a network. In the TRL/CRL/SRL model, this manifests as a low CRL despite mature technology.

Two Switzerland-specific findings go beyond the general infrastructure-needs evidence in the literature: according to a biogas expert from the Gaido thesis, only a small proportion of Swiss agricultural biogas

[39] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2026:616:FIN

plants meet the prerequisites for CCS integration (Gaido 2026; ZHAW 2024), which systematically prevents economies of scale. The Swiss support system rather prevents those small agricultural projects as it is focussed on large point sources like waste incineration and cement plants, which are consistent with the Swiss federal roadmap, where waste-incineration and cement plants received binding sector agreements or industry roadmaps for 2030, while agricultural biogas-based capture remained at the stage of a non-binding funding-tender assessment (Swiss Federal Council 2022, pp. 12–13, 15). The expert further points out that the current rail transport pathway to storage sites abroad accounts for a substantial share of total project costs (BAK Economics & dena 2023). This practitioner's experience is that the voluntary carbon market alone is not a sustainable foundation for a viable business model. Instead, the more promising path may lie in embedding BECCS within agricultural supply chains, where a carbon removal linked to a specific farm or product carries more value than an anonymous certificate sold to a financial institution, because the connection between removal and origin is direct and verifiable.

In practice, two financing structures are emerging: first, an upfront investment model, in which the end customer finances the capture infrastructure and receives certificates at a lower per-unit cost, while the plant operator receives an operating fee without bearing financial risk; and second, a long-term offtake agreement, in which the end customer commits to purchasing all certificates over 10–15 years at a somewhat higher price to compensate the operator's financing costs. Both models rest on full cost transparency as a competitive advantage, particularly relevant for non-profit operators who can openly disclose their production costs and negotiate certificate prices on that basis (World Economic Forum (WEF) 2026).

These assessments should be understood as supplier perspectives that require further verification. They nevertheless consistently illustrate that the infrastructure bottleneck requires coordinated state-led development.

2.4.11 Main conclusions and future research

Timing: BECCS is technologically mature at component level – CO_2 scrubbing, pressure swing adsorption, membrane and cryogenic separation are all established industrial processes – but unlike biochar or TCCS it cannot be deployed independently, because it depends on CO_2 transport and geological storage. The chicken-and-egg problem of transport infrastructure is consistently identified as the most critical bottleneck: no investor builds a CO_2 pipeline without guaranteed utilisation, and BECCS investors do not invest in capture technology if they do not know how to reach storage. Switzerland is currently at the start of a pioneering phase: the VBSA branch agreement commits waste-to-energy operators to at least one CCS plant of ≥100,000 tCO_2/year by 2030, the KVA Linth project has been technically specified but could not secure financing in time, and the first publicly funded Swiss BECCS project (Regionalwerke Baden, Otelfingen biomass power plant) received a positive ITINERO decision only in March 2026. Against the Federal Council's interim targets of 500,000 t by 2030 and 1.2 Mt by 2035, the pace of realisation, rather than technical feasibility, is the binding constraint.

Potential: The largest biogenic CO_2 potential in Switzerland lies in waste-incineration plants (around 2,000 kt/year at a 50 % biogenic fraction), followed by future biomass gasification (up to about 600 kt/year, 100% biogenic fraction), cement plants (around 250 kt/year at around 10 % biogenic fraction) and larger wastewater treatment plants (around 120 kt/year, 100% biogenic fraction). These figures may be reduced if the captured CO_2 is diverted to PtX applications for seasonal flexibility, and rise again if the CO_2 is recaptured when PtX products are centrally converted.

Feedstock: The most consequential open question for BECCS is not how much CO_2 can be captured but whether combustion is the right use of the biomass at all. Wood can be used for construction, burned, gasified, pyrolysed or hydrothermally carbonised, and each of the pathways produces a different combination of construction materials or energy, chemicals and solid carbon. Where BECCS competes with biochar and gasification-to-chemicals, our modelling shows different optimum utilisation ratios depending on the scenario. However, our modelling does not take geographic and infrastructure into account. Therefore, the results are unlikely to be uniform across Switzerland: the best use of a given assortment (energy wood, residues after cascade use) depends on regional boundary conditions such as existing plant and grid infrastructure, the availability of heat sinks, and the alternatives available for meeting local energy demand. Future research therefore needs to use a more regional and infrastructure disaggregated model, to identify regional and seasonal specific solutions.

CCS energy consumption: A conflict of objectives runs through all BECCS applications and is insufficiently addressed in current assessments: carbon capture reduces the thermal and electrical

output of a waste incineration plant. Where the replacement energy comes from, and what the overall environmental balance is if additional fuel – in the worst case fossil fuel – must be burned to secure winter heat, is not systematically quantified. This is a still a research gap which DeCIRRA was not able to answer:

- How do we resolve the following conflict of objectives: CCS reduces the thermal and electrical output of a waste incineration plant. Where does the replacement energy for this come from or what is the overall environmental impact if a higher quantity (of fossil fuels at worst) is then burned to ensure heat in winter? What are the environmental impact points for this (e.g. if district heating had to be generated using fossil fuels due to CCS operation in winter)?

- Which energy flows make more sense overall, are more resource-efficient and/or more climate-friendly: additional electricity/heat generation to compensate for the energy required for carbon capture, or not using carbon capture and using less energy instead?

Costs: Capture costs scale inversely with CO_2 concentration, so processes in which CO_2 arises as a concentrated co-product – gasification, anaerobic digestion, fermentation – have the cheapest capturing cost, while flue gases and cement kiln off-gases are considerably more expensive and they also need space. As the costs are still high, BECCS is not viable without subsidies, a high CO_2 price, or long-term offtake agreements. As transport and storage form a substantial part of the costs, the availability of a CO_2 pipeline and storage agreements with neighbouring countries are important cost drivers.

Financing and cost allocation: The CO_2 infrastructure requires coordination and federal government-led development, which is now underway. For CCS, the current Swiss support architecture is oriented towards large point sources and thereby systematically disadvantages CCS for small agricultural biogas projects, of which only a small share meet the technical prerequisites for CCS integration in any case.

Who bears the operating costs of CCS at waste incineration plants remains unresolved and has a political dimension. The waste branch agreement covers construction but not operation, and the discussed solidarity levy across Swiss waste incineration plants lacked a legal basis and the process seems stuck. If the polluter-pays principle is applied consistently, the cost would ultimately fall on waste charges – an increase in the price of the refuse bag – which raises questions of distributional acceptability (see Section 4.2). Alternative models identified in the DeCIRRA work include upfront investment financed through an advance recycling fee (vorgezogener Recyclingbeitrag, vRB) to plastic packaging and other fossil-based waste. This approach needs further research, but would have the advantage that those who can influence the material choice are in charge of the payment. The interactions of such approaches with a potential integration of waste incineration installations into the ETS (in line with the EU Commission's July 2026 proposal) would also need to be analysed.

Accounting: IPCC guidance for national inventories is clear in principle – captured volumes are subtracted in the sector of capture and stored CO_2 is recorded in the storing country – but guidelines are missing for cross-border transfers, where either the capturing country claims the removal or the storing country accounts for it and sells it as an ITMO. This matters directly for Switzerland, which will store CO_2 abroad for the foreseeable future. The IPCC Task Force on National Greenhouse Gas Inventories is mandated to deliver a methodology report on CDR, CCS and CCU by the end of 2027, which is expected to resolve much of this. On the carbon market side many standards have been approved over the last years: Article 6.4 removal standards were adopted in October 2024 by UNFCCC, Puro.earth integrated the CCS+ BECCS framework in October 2025, BSI published a dedicated BECCS specification in July 2025, and the first CRCF delegated regulation certifying BioCCS was adopted in February 2026. The EU ETS revision proposal envisages to include removal units in the EU ETS by means of limited removal purchases managed centrally by the Commission itself, as well as a gradual phase-in of municipal waste incineration installations into the ETS. Adoption of the proposal will largely determine whether a compliance-market business case for BECCS emerges and will also have implications on the Swiss waste incineration plants.

Risks: Among the CMAs examined, BECCS with geological storage offers the highest durability, and reversal risk is not the problem. Attention should instead focus on quantifying and minimising the leaks that do occur – methane slip, incomplete capture, and losses during transport – and on the environmental risk of captured chemicals such as amines, since these directly reduce net removal. The unresolved accounting question is where leakage is attributed when transport and storage cross borders.

Regulation: The just released EU proposed regulation will allow EU ETS entities to compensate their fossil emissions with their own CRCF-certified permanent BioCCS removals. To avoid double counting, carbon removals units used for the purpose of compensating own emissions need to be cancelled from the Registry and are counted toward the overall number of removals allowed to be integrated into the ETS.

The revised CO_2 Act and the KIG are considered adequate for the pioneering phase to 2030, but no legal framework exists for scaling up thereafter. The forthcoming CCS framework legislation, due to enter consultation in 2026, and the mandate to the Federal Council under Motion 24.4256 to develop a national framework for CO_2 capture, transport and storage are therefore decisive. A further regulatory question emerged from the stakeholder work and extends beyond BECCS itself: How can the legislator ensure that climate-damaging installations – for example fossil-based district heating – cease to be economically attractive, so that operators switch to climate-neutral alternatives rather than locking in inflexible, long-lived fossil infrastructure.

Co-benefits: Capture at point sources exploits substantial synergies: CO_2 concentrations of 10–50 % against 0.04 % in ambient air reduce energy demand and cost relative to DAC, and heat integration with existing plants lowers them further. The ability to alternate between PtX conversion and sequestration at the same installation can deliver a double systemic benefit – flexible seasonal energy storage plus negative emissions – while improving plant utilisation, supporting sector coupling and defossilisation of hard-to-abate applications, and reducing energy import dependence. In future research models would need to capture that seasonable operation. Co-capture of dust, nitrogen and sulphur oxides improves air quality, and captured CO_2 provides a domestic industrial carbon feedstock, reducing dependence on carbon imports.

2.5 Direct Air Capture (DAC)

Among CDR options, DAC stands out for its ability to remove CO_2 directly from the atmosphere using chemical sorbents or solvents. Unlike nature-based solutions or BECCS, DAC is not constrained by land availability or competition with food production. It offers high flexibility in siting – ideally near low-carbon energy sources and CO_2 storage or utilisation infrastructure – and enables verifiable, permanent carbon removal when paired with geological storage.

This section covers recent technical and economic progress in DAC, including operational experience from the first commercial-scale plants, improvements in system design and performance, and economic numbers. It reviews technological fundamentals (solid sorbent S-DAC vs. liquid solvent L-DAC), deployment potentials, policy developments, and cost drivers. Particular attention is given to the latest cost estimates and main influencing factors under current market conditions.

An interactive DAC Calculator was developed as part of this report to perform techno-economic analysis of both DAC technologies. The tool enables real-time evaluation of Levelized Cost of Capture (LCOC), CAPEX/OPEX breakdowns, NPV, IRR, payback period, and key technical metrics. It incorporates realistic engineering parameters and allows users to test various scenarios relevant to Switzerland and Europe, including plant scale, energy prices, capacity factor, CO_2 credit price, and transport and storage costs. All formulas, assumptions, and sensitivity analyses are documented in Appendix 2.

2.5.1 General description

Direct air capture (DAC)-based technologies involve the contact of substantial volumes of air with sorbent chemicals, which undergo regenerative cycles to capture, concentrate, and securely store atmospheric CO_2. DAC overcomes the spatial and arable land limitations of afforestation and BECCS while offering significant siting flexibility wherever low-carbon energy and CO_2 storage/utilisation opportunities exist.

DAC is classified into two main types (see Figure 35): Low-temperature solid sorbent (S-DAC) and high-temperature liquid sorbent (L-DAC) technologies. **S-DAC** operates in batch mode with adsorption and regeneration at around 100°C using temperature or temperature-vacuum swings, typically with amine-functionalized porous materials. **L-DAC** uses a dual-loop alkaline solution process (e.g., potassium hydroxide) with high-temperature calcination (~900°C) for CO_2 release. Both technologies have demonstrated successful operation in European and North American climates, with ongoing testing in extreme conditions. Recent commercial plants confirm the maturity of modular designs, particularly in S-DAC.

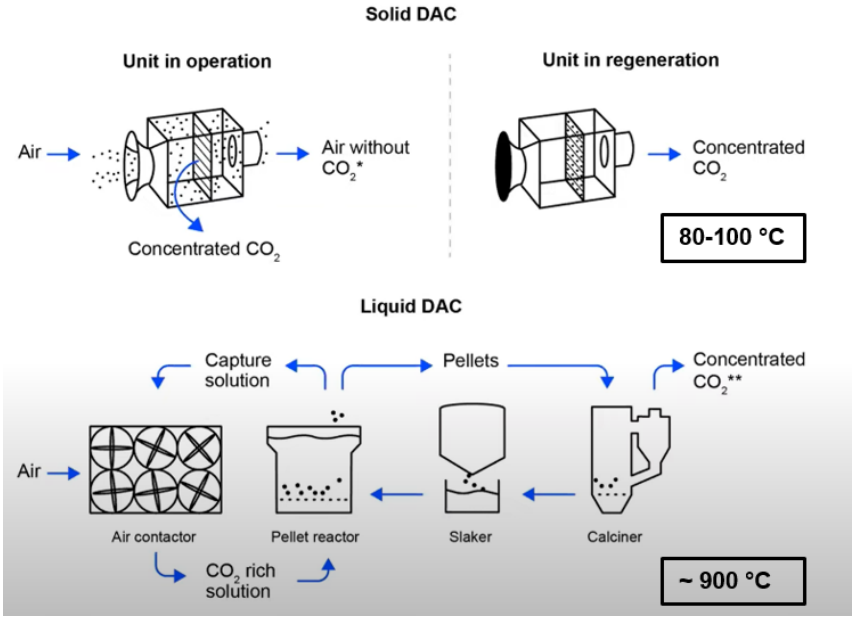


*Figure 35: S-DAC (top) and L-DAC (bottom) configurations (*IEA 2022, p. 22).

2.5.2 System boundaries, material and emissions flows, and main drivers

Main processes within the system boundaries of DACCS – irrespectively whether the DAC process is solvent- or sorbent-based – for accounting for effective CDR, climate impacts and other environmental burdens of DACCS include supply of heat and electricity for the DAC process, CO_2 transport and injection into geological reservoirs and the infrastructure construction and maintenance of the DAC unit as well as of CO_2 transport and injection (Figure 36). Furthermore, negligible leaking of CO_2 from the geological reservoir must be ensured via long-term monitoring.

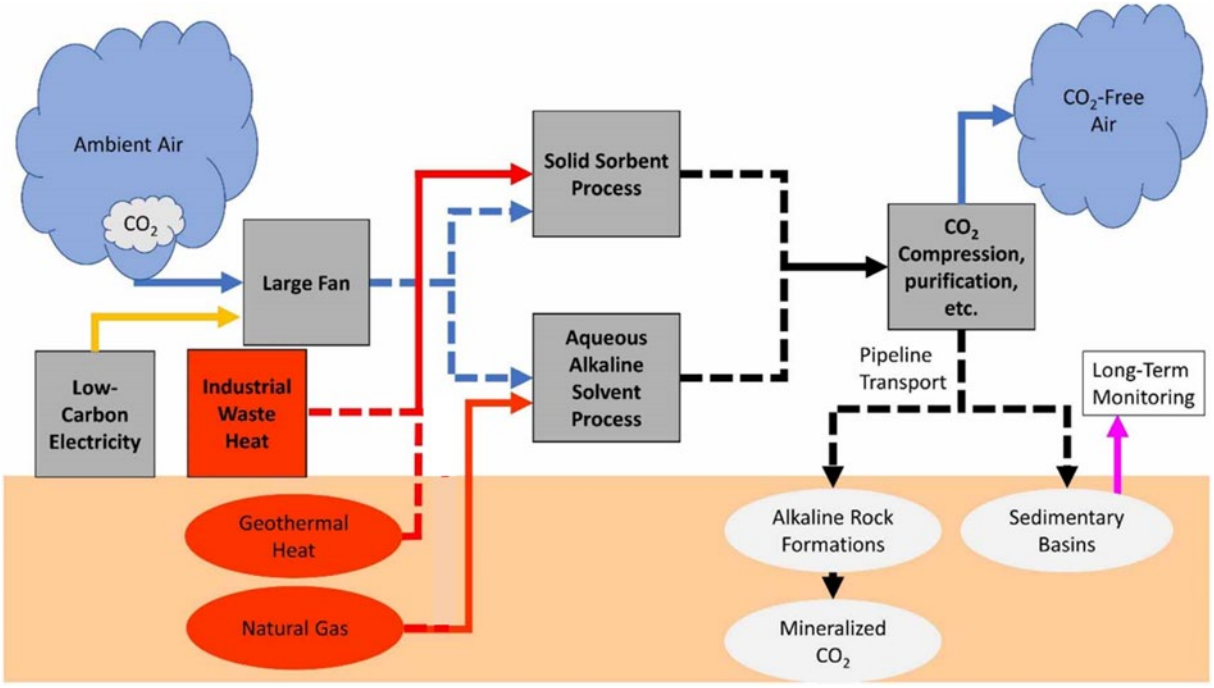


Figure 36: Schematic process diagram of DACCS systems (adapted from Sovacool et al. 2022).

Available LCA studies performed for both high- and low-temperature DAC processes (i.e., solvent- and sorbent-based, respectively) indicate that the energy sources used for the DAC process and their associated GHG emissions are the main driver for the effectiveness of DACCS-based CDR (Deutz and Bardow 2021; Qiu et al. 2022; Terlouw, Treyer, et al. 2021). High effectiveness of DACCS in terms of CDR can only be achieved if GHG emissions associated with heat and electricity supply for the DAC process are low.

2.5.3 Co-benefits

DAC technology offers several additional co-benefits, which are partly climate-relevant:

- **Carbon Removal (CCS)**: DAC enables the direct removal of carbon dioxide from the atmosphere, contributing to global efforts to reduce GHG emissions and combat climate change. When done at the sequestration site and renewable energy is available, ***no long-distance transport of CO_2 is needed***.
- **Carbon Utilisation (CCU)**: Captured CO_2 can be utilised in various ways, such as in the production of synthetic fuels, chemicals, or building materials, providing opportunities for carbon utilisation and ***reducing the reliance on fossil fuels.***
- **Renewable energy integration**: DAC plants must be powered by renewable energy sources, facilitating the integration of clean energy technologies and helping to achieve decarbonisation goals.

2.5.4 Risks and challenges

- **Environmental impact**: The construction, operation, and maintenance of DAC facilities may have environmental impacts, including land use, water consumption, and potential release of

chemicals used in the capture and storage processes. Ensuring proper environmental management and minimizing negative impacts is essential.

- **Energy intensive**: DAC processes typically require a significant amount of energy, which may predominantly come from non-renewable sources if not properly addressed, potentially offsetting some of the carbon reduction benefits.
- **Competition**: The service of DAC can also be done by Bioenergy CCU/CCS, using plants as DAC units.
- **Cost**: Current DAC technologies are expensive and not yet commercially viable at a large scale. Cost reduction and technological advancements are necessary for wider adoption.
- **Scale and deployment challenges**: Scaling up DAC technology to capture large volumes of CO_2 is a significant challenge. Building and deploying DAC plants at the required scale and in diverse geographical locations may pose logistical and infrastructure challenges.

2.5.5 Accounting

There is to date no inventory category into which DACS fits naturally. The IPCC guidelines provide, within each sector, subcategories for other measures. So, absent specific DACS guidance, countries report emissions and sinks as they judge most appropriate – for example reporting negative emissions under industry ("other") for CO_2 captured directly from air with the intent of storing it. For reporting the corresponding CO_2 storage, the same guidelines apply as for conventional CCS from point sources (Eggelston et al. 2006, Chapter 5).

As noted already in the sections on biochar and BECCS, an important development for the national-inventory accounting of all engineered removals is that the IPCC Task Force on National Greenhouse Gas Inventories has been mandated to deliver a methodology report on carbon dioxide removal, CCS and CCU by the end of 2027. This is expected to provide additional guidance on how removals from the various methods should be reported in national GHG inventories under the UNFCCC (Edwards et al. 2026), and should over time reduce the current ambiguities in inventory treatment of removals.

On the project side, the voluntary-market methodology landscape for DACS has matured considerably. Within the Verified Carbon Standard, the modular framework developed by the CCS+ initiative now includes a dedicated DAC module (VMD0056, "CO_2 Capture from Air (Direct Air Capture)," v1.0) that works together with Verra's general CCS methodology (Verra 2025b). Newer removal-focused registries have added DACS methodologies as well – including Absolute Climate, whose Direct Air Capture and Storage methodology (v1.0) was finalized in 2025 following public consultation (Absolute Climate 2025a, 2025b). And Puro.earth, in October 2025, integrated the CCS+ initiative's BECCS and DACCS methodology framework into its own certification and issuance framework, allowing suppliers to issue Puro CO_2 Removal Certificates (CORCs) based on the CCS+ methodologies via the Puro Registry – a step toward reducing fragmentation and aligning voluntary certification with the EU CRCF and Article 6 requirements (Puro.earth 2025). Climeworks has also pursued DACS transactions under the Paris Agreement carbon markets, including a pilot bilateral transaction under Article 6.2 (supported by Perspectives).

At the framework level, two developments stand out. First, the EU CRCF's first delegated regulation (February 2026) includes a certification methodology for DACCS, giving DACS removals a formal EU certification route alongside BioCCS and biochar (European Commission 2026a). Second, under the Paris Agreement Crediting Mechanism the Article 6.4 Supervisory Body adopted its removals standards in October 2024 (endorsed at COP29), with a DACCS methodology under development but not yet adopted as of mid-2026.

2.5.6 Potentials

DAC's long-term potential in net-zero pathways remains robust but is increasingly framed by the need for rapid near-term scale-up. According to the latest report from the WEF (World Economic Forum et al. 2026), around 2.1 Gt CO_2/year are already being removed globally, predominantly through conventional land-based methods. However, between 6.5 and 13.3 Gt CO_2/year of total CDR will be required by mid-century under the latest State of Carbon Dioxide Removals report's highest ambition scenario (which now assumes overshooting the Paris Agreement's 1.5°C goal before meeting it later in the century), with engineered solutions like DAC playing an essential role (estimated at 0.9–6.4 Gt (median 3.5 Gt)) in balancing residual emissions from hard-to-abate sectors such as aviation, shipping, and cement (Edwards et al. 2026, p. 192).

The International Energy Agency's Net Zero Emissions by 2050 (NZE) scenario projects DAC deployment reaching around 1 Gt CO_2/year by 2050, accounting for a substantial share of cumulative removals. By 2100, 1.8 Gt CO_2/year removals from DAC are reached under the NZE scenario. If all energy needed for such deployment were provided by solar PV, this would require about 3.3 million ha of land, somewhat more than Belgium's land area (IEA 2025, p. 234).

A more fundamental objection has recently been raised against DAC's role in climate strategy. Jia and Kirk (2026) argue that the constraint is thermodynamic rather than engineering-related: because atmospheric CO_2 is present at only ~0.04 %, the entropy-of-mixing penalty sets a physical floor on the energy required, and commercial plants accordingly demonstrate 1,500–3,000 kWh per tonne of CO_2 captured and stored, one to two orders of magnitude above capture at concentrated point sources (6.3–25.2 kWh/t at coal gasification plants, 31.5–44.1 kWh/t at direct coal combustion facilities). Scaled to the lower bound of the IPCC's mid-century removal requirement of 7 Gt CO_2/year, this would imply roughly 194,000 plants of Mammoth's size and around 17,500 TWh/year – more than half of global electricity generation in 2024 (~30,000 TWh). Even limiting DAC to 3 Gt CO_2/year to balance residual emissions from aviation, shipping and cement would consume some 7,500 TWh, a quarter of global electricity. The authors conclude that advances in sorbent materials improve capture capacity but do not alter this constraint, and that overreliance on DAC risks institutionalising energy inefficiency and diverting clean electricity away from direct decarbonisation. They therefore advocate prioritising emissions prevention at source together with energy-positive removal pathways such as biochar, whose pyrolysis by-products (syngas, bio-oil) yield rather than consume energy. Importantly, their argument does not exclude DAC entirely: they accept some deployment in specific contexts, namely where ultra-low-cost stranded renewable energy or long-duration storage is available and no clean energy is diverted from displacing fossil fuels. For Switzerland, where neither cheap surplus electricity nor proximate geological storage is available, this reinforces the model findings which do not predict any DAC in Switzerland.

Based on installations already in operation and under construction, it is estimated that DAC deployment reaches 0.55 Mt CO_2/year in 2030 (Edwards et al. 2026, p. 179). Based on company announcements, which are highly uncertain, annual removals from DACCS could reach 3.76 Gt CO_2 per year by 2050 (Edwards et al. 2026, p. 77).

Recent analyses emphasise that near-term deployment success, rather than solely long-term targets, will determine feasibility. Mammoth and STRATOS provide the first real-world data on modularity, capacity factors, and integration with renewable energy and storage, informing learning curves and supply-chain development. However, challenges persist: lead times of 2–6 years for large plants, dependence on policy-driven demand (e.g., US 45Q tax credit at 180 US$/t and EU CRCF certification), and the need for low-carbon energy at scale (Kashtan et al. 2026).

In a study conducted by Shayegh et al. (2021), 18 experts from various industries and academia were interviewed regarding negative emissions and DAC technologies, as well as their economic and policy aspects. The findings indicate that half of the experts (50%) believe that the lack of supportive policies and regulations will impede the future growth of DAC technologies. Additionally, 44% of the experts emphasised the importance of innovation in reducing the energy intensity of the DAC process and integrating it with renewable energy sources. Surprisingly, the study reveals that "Social acceptability" and "Storage capacity" received lower percentages of concern from the experts, with only 22% and 17% of votes, respectively. This suggests that the experts are confident that there is sufficient geological storage capacity for permanent CO_2 sequestration and that the general public is willing to accept DAC, as long as there is adequate policy and regulatory support. Figure 37 illustrates the ranking of these limiting factors.

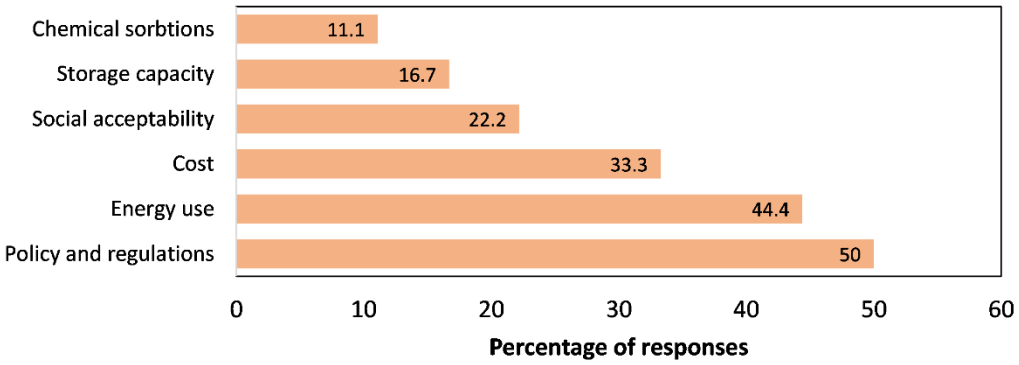


Figure 37: Experts' responses on the DAC development limiting factors (adapted from Shayegh et al. 2021).

2.5.7 Estimates of costs and main drivers

DAC remains one of the most capital-intensive engineered CDR pathways. High capital expenditure requirements, combined with significant energy demands for the adsorption/desorption cycle, result in current price levels of several hundred dollars per tonne of CO_2. This is reflected in the technology's net carbon efficiency of only 55–80 %, which is notably lower than BECCS (85–100 %) or biochar (90–100 %) primarily because of the high energy and capex intensity of the capture and regeneration process (World Economic Forum et al. 2026, p. 11). Early commercial DAC projects therefore rely heavily on advance offtake agreements and prepayments.

Techno-economic studies project significant cost reductions with scale, learning, and improved sorbent materials. First-of-a-kind DAC costs are estimated at 400–1000+ US$/tCO$_2$ or 350–550 US$/tCO$_2$ (lowest-cost renewables), falling to 194–230 US$/tCO$_2$ for nth-of-a-kind (NOAK) plants at 1 Mt CO$_2$/year scale under favourable conditions (IEAGHG 2021). Climeworks targets 250–350 US$/t through Generation 3 technology and further modular scale-up (Climeworks 2024a). Achieving these numbers will require large-scale deployments for economies of scale (Climeworks, personal communication). Long-term literature consensus points to 100–200 US$/tCO$_2$ under ambitious assumptions (low-cost renewables, high-capacity factors, and breakthrough energy efficiency of ~800 kWh/tCO$_2$), though real-world achievement will depend on policy support and supply-chain maturation.

The choice and performance of the sorbent/solvent material rank among the most consequential individual cost drivers, especially in S-DAC systems. Techno-economic analyses consistently show that sorbent properties – working capacity at ~400 ppm CO_2, regeneration energy (typically 4–10 GJ/tCO$_2$), kinetics (cycle time), water co-adsorption, and long-term stability (>1,000–5,000 cycles before significant degradation) – directly determine plant sizing, energy intensity, material replacement frequency, and both CAPEX and OPEX. In solid sorbent configurations, adsorbent costs and lifetime can represent a dominant share of total costs; sensitivity analyses indicate that targeted improvements in these parameters offer the highest leverage, potentially reducing levelized costs by 25% or more (IEAGHG 2021).

Solid amine-functionalized sorbents dominating commercial deployments due to their modularity, lower regeneration temperatures (80–120°C), and compatibility with temperature-vacuum swing adsorption (TVSA). Recent scientific literature emphasises ongoing optimisation of these materials, particularly amine-impregnated or grafted supports (e.g., silica, alumina, or structured composites), which achieve working capacities of 0.5–2.5 mmol/g at ~400 ppm CO_2. Key challenges include oxidative degradation, water co-adsorption, and capacity fade over cycles (Holmes et al. 2024; Zentou et al. 2025).

Recent developments focus on structured sorbents to accelerate cost reductions. Climeworks' Generation 3 technology, validated in large-scale testing (>1,300 cycles), uses novel structured adsorbents that double CO_2 capture throughput per module and halve overall energy consumption compared to Generation 2, which is based on non-structured materials. The main enablers of the increased efficiency of Generation 3 technology are faster kinetics, lower pressure drop, improved heat transfer, as well as significantly extended sorbent lifetime (Climeworks 2024a, 2024b).

Metal-organic frameworks (MOFs), porous organic polymers, and hybrid materials show promise for higher capacities, faster kinetics, and reduced regeneration energy, while liquid alkaline solvents (e.g., KOH-based) benefit from process optimisations for high-throughput applications. Sensitivity analyses in techno-economic studies confirm that gains in capacity, kinetics, stability, and cost per kg of sorbent offer the greatest leverage for bringing levelized costs toward the 100–200 US$/t$CO_2$ target (Qiu et al. 2025).

Beyond sorbent/solvent performance, capital expenditure is another main cost drivers in DAC systems. CAPEX for air contactors, fans/blowers, regeneration equipment, and balance-of-plant infra-structure often dominates early-project costs (frequently 40–60% or more of levelized cost in FOAK plants). Processing ultra-dilute atmospheric CO_2 (~400 ppm) requires moving enormous air volumes, driving large contactor arrays and high fan power. Energy consumption, particularly electricity for air handling and low-grade heat (or high-temperature for liquid systems) for regeneration, can account for 30–50% of long-term costs depending on technology and configuration (IEA 2022). Location-specific variables further modulate these drivers: access to low-cost renewables, ambient humidity/temperature (affecting kinetics and water co-adsorption), and proximity to CO_2 storage sites (adding transport/compression costs).

Other notable drivers include financing risks and operational expenditures. Limited debt access, shorter offtake contracts, and perceived technology risk elevate the cost of capital (WACC), especially for early projects. Fixed OPEX (maintenance, labour) and variable costs (sorbent replacement, water in some systems) add further pressure, while contingencies for uncertainties can rep-resent 15–25% of FOAK CAPEX. TEAs emphasise that economies of scale, learning-by-doing, and supply-chain maturation will reduce CAPEX by 50–80% at gigatonne scale, but these gains depend heavily on sustained deployment and innovation (IEAGHG 2021). Integration with cheap waste heat or optimised renewables can significantly lower effective energy costs.

2.5.8 DAC calculator tool

To operationalise these insights for the Swiss and European context, this report introduces the DAC Calculator, an interactive techno-economic analysis tool developed specifically for the DeCIRRA project. Built with realistic 2026 engineering parameters, the tool evaluates both S-DAC and L-DAC plants in real time. Users can adjust key variables including plant capacity (10–2000 kt CO_2/year), electricity and heat prices, maintenance rate, capacity factor, CO_2 credit price, and transport and storage costs. Outputs include Levelized Cost of Capture (LCOC), detailed CAPEX/OPEX breakdowns, NPV, IRR, payback period, cost waterfall and OPEX percentage charts, plus technical metrics (energy consumption, water use, land footprint, and net CO_2 removal). Detailed formulas, assumptions (WACC, lifetimes, energy demands), and sensitivity analyses are provided in Appendix 2.

Case study 1: Project Cypress- 1 Mt CO_2/year, S-DAC, Louisiana, USA

Project Cypress is one of the leading U.S. Regional DAC Hubs, led by Battelle in partnership with Climeworks and Heirloom. The project aims to capture and permanently store 1 Mt CO_2/year using advanced Generation 3 solid sorbent (temperature-vacuum swing adsorption) technology. It benefits from Louisiana's existing infrastructure, favourable geology for saline storage, and access to renewable/low-carbon energy via Entergy. Project Assumptions:

- Electricity price: 45 US$/MWh (renewable PPA mix – solar/wind)
- Heat: 35 US$/$MWh_{th}$ (low-grade natural gas or industrial waste heat)
- CO_2 credit / removal payment: 180 US$/t$CO_2$ (blended 45Q-style incentive + voluntary market)
- Other parameters: Standard tool defaults (capacity factor 85%, discount rate 8%, lifetime 25 years)

At LCOC of 187 US$/t$CO_2$ for a 1 Mt CO_2/year scale, project Cypress exhibits highly challenging economics under current market and policy conditions. The analysis reveals a breakeven CO_2 credit price of 367 US$/t and a simple payback period of 95 years, indicating that the project would not be commercially viable without significantly higher incentives or accelerated cost reductions. Even with favourable energy prices in Louisiana, the facility generates strongly negative cash flows, resulting in a 25-year NPV of approximately –1.7 billion US$.
Capital expenditure remains the dominant cost driver, contributing 57% of gross annual costs. This is followed by heat (~15%) and transport and storage (~9%). The overwhelming influence of upfront capital underscores the capital-intensive nature of current solid sorbent DAC technology, even at megaton scale.

Case study 2: Project Stratos, 500 kt CO_2/year L-DAC facility in Ector County, Texas, USA

Project Stratos, developed by 1PointFive in Ector County, Texas, is a pioneering 500 kt CO_2/year L-DAC facility using Carbon Engineering's potassium hydroxide solvent technology. The plant captures CO_2 from ambient air and plans permanent storage in local saline formations. Other assumptions: solar PV electricity at 35 US$/MWh, natural gas heat at 45 US$/$MWh_{th}$, 85% capacity factor, carbon credit of 180 US$/$tCO_2$.

The LCOC for Project Stratos reaches 305 US$/$tCO_2$. This result highlights severely challenging economics, even with highly favourable energy inputs in Texas. The project requires a breakeven CO_2 credit price of 485 US$/t to achieve zero NPV, while current incentives at 180 US$/t result in a deeply negative 25-year NPV of –1.385 billion US$, zero IRR, and a simple payback period of 113 years. Capital expenditure overwhelmingly dominates the cost structure, contributing 58% of the gross levelized cost. This is followed by heat (~20%) and transport and storage. The extreme capital intensity of the liquid solvent process, combined with high-temperature calcination energy demand, makes L-DAC particularly sensitive to upfront investment costs at this scale.

Case study 3: Swiss S-DAC deployment scenario

To evaluate deployment feasibility in the Swiss context, the DAC Calculator was used with adapted parameters. Switzerland's temperate climate, access to low-grade waste heat (from incinerators, industry, and CHP plants), and high renewable electricity share provide technical advantages for solid-sorbent S-DAC, but higher energy prices and limited domestic storage pose economic challenges. Key assumptions:

- Plant scale: 100 kt CO_2/year (S-DAC, Gen 3 sorbent)
- Electricity: Swiss renewable PPA at 80 US$/MWh
- Low-grade heat: Waste-heat integration at 35 US$/$MWh_{th}$ (from incinerators/CHP)
- Capacity factor: 85%
- CO_2 credit: 180 US$/$tCO_2$
- Transport & storage: 60 US$/$tCO_2$ (cross-border)
- Other: WACC 8%, 25-year lifetime

The analysis yields a LCOC of 354 US$/$tCO_2$. Excluding transport and storage costs, the LCOC drops to 294 US$/$tCO_2$. The breakeven CO_2 credit price required to achieve zero NPV is 534 US$/$tCO_2$ (or 474 US$/$tCO_2$ without T&S). Under current incentive levels, the project never pays back within its 25-year lifetime, resulting in a strongly negative NPV with CAPEX as the dominant cost driver.

2.5.9 The role of DACC across scenarios

In none of the four scenarios DACC has been deployed within Switzerland. The reasons for not deploying DACC in Switzerland are mainly economical and related to CO_2 storage availability.

Technically, Switzerland offers favourable conditions for solid sorbent S-DAC systems. The country's temperate and relatively humid climate supports efficient adsorption kinetics for amine-functionalized materials. S-DAC's low regeneration temperature (80–120°C) aligns well with available low-grade waste heat sources. Burg et al. (2024) estimate a total technical waste-heat potential of around 37 TWh/year from municipal incinerators, industrial processes, wastewater treatment, and combined heat and power facilities. However, only a limited share of this potential fall into the 80–120°C temperature range suitable for S-DAC, and this heat is subject to strong competition from other applications such as district heating and industrial processes.

Electricity needs can be met through Switzerland's high share of renewable generation (hydro ~60% of electricity production) via dedicated power purchase agreements, enabling high net removal efficiency (>90% with low-carbon energy). Modular S-DAC designs enable flexible siting near existing infrastructure, minimizing land use and integration costs.

However, domestic geological storage is limited. Switzerland's long-term strategy foresees 2–5 Mt CO_2/year of domestic storage by 2050 (mainly via mineralisation and saline formations), with total CO_2 storage demand estimated at ~12 Mt CO_2/year including hard-to-abate emissions and removals (Becattini 2025). This will require substantial reliance on cross-border transport and international cooperation (e.g., bilateral agreements with Norway or other North Sea storage hubs).

Economically, Swiss industrial electricity and low-grade heat prices are moderate to high compared to global benchmarks, which represents a notable challenge for DAC deployment. While access to low-grade waste heat from incinerators, industrial facilities, and combined heat and power plants can help reduce the thermal energy component – which typically accounts for 40–60% of total energy demand and a significant share of OPEX in S-DAC systems – the actual cost savings depend on site-specific integration and may be more modest than in locations with abundant very cheap energy. The Hinwil plant has demonstrated the technical feasibility of waste-heat coupling, but scaling this approach remains limited by available heat volumes and competition with other uses. When combined with innovation funding under the Climate and Innovation Act and ongoing Gen 3+ sorbent improvements, modest-scale S-DAC facilities (10–100 kt CO_2/year) could be pursued as innovation and learning platforms in the coming decade, though their economic viability will require substantial public support. Larger deployments would face considerable hurdles and would heavily depend on international CO_2 storage partnerships as well as further cost reductions.

2.5.10 Relevant actors and current deployment status

DAC has transitioned from pilot-scale demonstration to the early commercial phase, with global operating and near-operational capacity increasing from 10 kt CO_2/year across 18 small facilities in 2022 to an estimated 569 kt CO_2/year by the end of 2025 (AlliedOffsets 2025; Green Fuel Journal 2026) – equivalent to the annual CO_2 emissions of one large Swiss cement plant (e.g., Wildegg). According to the IEA CCUS Projects Database as of 2026, 79 DAC plants (including pilots and commercial facilities) are expected to be operational, though the majority remain at modest scale (IEA 2026b).

Among the leading commercial DAC developers, Climeworks AG (Switzerland, solid-sorbent S-DAC) and 1PointFive / Carbon Engineering (USA/Canada, liquid-sorbent L-DAC) stand out as the most advanced actors. Climeworks' Mammoth plant in Iceland, with a nameplate capacity of 36,000 tCO_2/year, commenced operations in 2024 and is currently in active ramp-up, with core infrastructure and 90% of systems operational (Climeworks 2024c). Powered by renewable geothermal energy and paired with Carbfix mineralisation for permanent geological storage, Mammoth represents a tenfold scale-up from the earlier Orca plant (4,000 tCO_2/year) and has yielded critical operational data on modular design, sorbent durability, and real-world performance in northern climates (Climeworks 2024a, 2024c). The reasons why the ORCA plant has not delivered the expected amounts are manyfold:

1. Real-world operating conditions forced regular plant shutdowns, especially in the first months of operation (e.g., due to snowstorms)
2. The sorbent materials used in Orca represent the state-of-the-art of about 2019. Since then, significant improvements have been made to the materials to increase quality and improve batch-to-batch variability
3. Orca incurred significant losses of captured CO_2 (CO_2 recovery losses), where captured CO_2 had to be vented into the atmosphere as it did not meet the purity standard for storage. The Mammoth plant was simplified and uses an absorption column in place of a liquefaction process that significantly lowers the dependence on CO_2 purity, addressing the root cause of recovery losses.

Building on these operational lessons, Climeworks has since pivoted from a scale-first to a learn-first strategy, prioritising cost reduction and technological iteration over the construction of ever-larger facilities. Rather than pursuing maximum capacity, the company now aims to demonstrate at smaller scale that capture costs can be brought down to approximately 400 US$/$tCO_2$ for its next-generation technology. Central to this approach is a programme of rapid engineering iteration: seven smaller DAC plants in Zurich have collectively generated over eight million data points, enabling more frequent adjustments to sorbent composition and system design. A world-leading DAC innovation centre has been inaugurated in December 2025, allowing for fast iteration loops from lab-scale to mid-scale (Climeworks 2025). On the project development side, geographic priorities have shifted, with Canada gaining relative weight over the United States. In the US they experienced a long political uncertainty around the retention of Inflation Reduction Act funding, of which they were granted 500 million US$.

In parallel, 1PointFive's STRATOS facility in Ector County, Texas – the world's largest planned DAC plant using Carbon Engineering's high-temperature liquid technology – is in final commissioning, with Phase 1 startup targeted for Q2 2026 and full commercial operation expected by the end of 2026 (1PointFive 2026). Designed for 500 kt CO_2/year upon completion (with potential expansion to 1 Mt CO_2/year), STRATOS incorporates geological storage and co-captures process emissions from the calciner, achieving net-zero power emissions through a combination of on-site and off-site renewables.

The project, with a capital investment of US$ 1.3 billion, is supported by offtake agreements from major buyers including Microsoft, Amazon, and BlackRock (Regreener 2026).

Further momentum is provided by U.S. Department of Energy-funded DAC hubs (e.g., Project Cypress in Louisiana, targeting 1 Mt CO_2/year by 2030 with Climeworks involvement) and emerging players such as Heirloom Carbon (accelerated mineralisation DAC) and Global Thermostat (S-DAC) (IEA 2026b). According to IEA data (World Economic Forum et al. 2026, p. 16), planned projects, collectively, could approach 65 Mt CO_2/year by 2030 if all advance to operation. However, with global DAC capacity still below 1 Mt CO_2/year in 2026, this scenario remains highly optimistic. Most projects are still in early development, and their realisation will critically depend on sustained policy support, robust demand for verified removals, and accelerated progress in financing and execution.

2.5.11 National and international policies and incentives

In Switzerland

DACS is currently not incentivised in Switzerland in a systematic, technology-specific manner. However, the Climate and Innovation Act (effective 1 January 2025) strengthens support through a national climate fund, innovation funding, and targeted procurement for carbon removal (Robinson 2025). The government continues to back Climeworks via R&D grants, pilot support, and public procurement commitments for net-zero balancing. Switzerland has launched tenders for carbon management solutions aiming for 500,000 tCO_2 storage capacity by 2030, with up to CHF 100 million allocated specifically for CCS and CDR projects under the Act's CHF 1.2 billion innovation package (Carbon Direct 2025). Corporate net-zero roadmap mandates now explicitly include high-quality removals, though these remain largely supply-push oriented (Planet2050 2025).

Such supply-side support alone, however, cannot deliver the order of magnitude scaling that DACS is expected to require.

A more concrete step came in late 2025, when the Federal Council opened a consultation on how the federal administration is to meet its own net-zero target for 2040 (ahead of the national 2050 goal). The proposed regulatory changes cover a range of questions – including which emissions are in scope, the net-zero roadmaps to be prepared, and the associated accounting rules – of which the purchase of carbon dioxide removals is one element (Swiss Federal Council 2025a, 2025c). Under that element, the administration would buy removals to balance its residual emissions: the FOEN would act as purchaser, acquiring removals generated in Switzerland (approved as attestations by the Compensation Office jointly run by FOEN and SFOE) or abroad in the form of Internationally Transferred Mitigation Outcomes (ITMOs), offsetting the administration's residual Scope 1–3 emissions under Article 10 of the Climate and Innovation Act. The consultation ran until 12 February 2026. If implemented, this would create a first, if limited, source of public demand for DACS and other durable removals in Switzerland.

More broadly, Switzerland's long-term climate strategy anticipates a need for around 7 Mt CO_2/year of removals by 2050, roughly 2 Mt domestically (mainly via BECCS) and 5 Mt abroad, part of it potentially via DACS.

At the same time, the difficulties of scaling DACS have become more visible. Climeworks, the flagship Swiss developer, cut about 22% of its workforce in 2025 (around 106 positions, some 78 of them in Switzerland) amid market and policy uncertainty and paused its planned US expansion, while its Orca and Mammoth plants in Iceland have so far operated well below nameplate capacity (SWI swissinfo.ch 2025). This underlines that, absent sustained demand and cost reductions, supply-side support will not by itself make DACS commercially viable.

Internationally

DAC's potential contribution to climate change mitigation is increasingly recognised, supported by initiatives from both public and private sectors. In 2021, the United States allocated US$ 3.5 billion to establish four Regional DAC Hubs and introduced a DAC Prize program offering US$ 100 million for commercial-scale projects and US$ 15 million for pre-commercial projects. The United Kingdom has also dedicated GBP 100 million to CDR approaches, including DAC. Funding programs supporting DAC development and deployment have been initiated in Australia, Canada, the EU, and others.

The US Regional DAC Hubs program has since passed through considerable turbulence. Following cancellations and reviews of clean-energy grants in late 2025, the Department of Energy confirmed in early 2026 that it would retain funding for the two largest, commercial-scale hubs: Project Cypress in Louisiana (up to US$ 600 million; partners include Battelle, Climeworks and Heirloom) and the South Texas DAC Hub (up to US$ 500 million; led by 1PointFive/Occidental). It cut a number of smaller DAC awards and reprogrammed around US$ 1 billion of unobligated DAC-hub funds to other offices. Even the retained awards remained subject to administrative finalization and thus some uncertainty (Mitchell et al. 2026; Ranevska 2026).

Beyond such investment support, the internationally most substantial incentive for DACS remains the US Section 45Q tax credit, which under the "One Big Beautiful Bill Act" of July 2025 was maintained at US$ 180/tCO_2 for DAC with dedicated geological storage. The same Act raised the rates for CO_2 utilisation and enhanced oil recovery to parity with permanent storage (Min 2025).

The United Kingdom, for its part, has developed a dedicated Greenhouse Gas Removals (GGR) business model: it offers 15-year revenue support through a contract-for-difference mechanism, with the reference price linked to the price of GGR credits in the voluntary carbon market, complemented by the roughly GBP 60 million DAC/GGR Innovation Programme. The British Standards Institution also published an interim DACCS quantification specification (BSI Flex 2007 v1.0:2025-07) in July 2025 (UK Government 2025; BSI 2025b).

To achieve scaling and cost reductions, DACS ultimately requires market-based demand. Climeworks and other developers have benefited from voluntary advanced market purchase agreements (in some cases securing demand up to eight years out). However, at an average of 593 US$/t in 2025, credit prices remain well above those of other mitigation categories (Edwards et al. 2026), and demand is still highly concentrated in the US (where 98% of purchases in 2024 occurred), highlighting the crucial role of the 45Q credits in promoting this market (World Economic Forum et al. 2026). Accordingly, DAC remains the removal technology most reliant on government funding (approx. 10 billion US$) relative to private funding (about 4.1 billion US$) (World Economic Forum et al. 2026).

Over time, DACS costs may fall to meet gradually rising prices in compliance carbon markets, which could unlock broad sustained demand – for example through international transfers under Article 6 of the Paris Agreement, or through emissions trading systems such as the Swiss ETS and the EU ETS to which it is linked. In the EU, the CRCF Regulation now provides a certification route for DACCS removals (see accounting rules below), and the Commission's EU ETS revision proposal from July 2026 introduces an increase in the ETS cap to be used by the Commission for the purchase of a limited amount of CRCF-certified BioCCS and DACCS domestic removals.[40]

2.5.12 Business models

DACCS business activities are split primarily between technology and certificate providers. Switzerland hosts only two genuine DAC technology startups: Climeworks AG and forty-four AG, but neither is currently scaling operations within the country. Climeworks, as a pioneering company in the field, installed the world's first commercial DAC pilot in Hinwil, Switzerland, and continues to operate several pilots while maintaining its entire research and development team in the country. The DACC technology is currently estimated at TRL 6–8, or possibly 9 depending on the specific methodology and technology variant, for example, solid sorbents versus electrochemical approaches (Gaido 2026; Cames et al. 2023, p. 106; Ishaq & Crawford 2025, p. 3666; van der Spek et al. 2025). Certificate-based DACCS models require CO_2 prices of at least 400–500 US$/t to achieve long-term financial viability (Lagler 2025).

According to Gaido (2026), DACCS in general faces an institutionalized funding gap between well-covered basic research and structurally underfunded field demonstration. In technology-neutral funding programmes, DACCS is apparently systematically disadvantaged, as the technology competes directly with cheaper climate technologies – a finding consistent with the theoretical Valley-of-Death logic, even though it is based on a single interview partner. The stakeholder interviewed reports significantly higher success rates in technology-specific calls for tender. The suspension of programmes such as the Swiss Federal Office of Energy's Pilot and Demonstration Programme could further widen such gaps across technologies.

[40] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2026:616:FIN

More broadly, DACCS remains one of the most expensive and energy-intensive CDR technologies. It is heavily dependent on access to cheap renewable electricity and a proximate deep underground storage site – two preconditions that are currently unavailable in Switzerland. Without a regulatory framework or direct subsidies, DACCS has no viable business model at present, not in Switzerland, but also not abroad. Scaling would require the development of very large-scale DAC facilities as well as the corresponding storage infrastructure (Gaido 2026; Betz et al. 2023, p. 71).

Technology-oriented providers generate revenues through equipment sales and licensing, with CO_2 certificate price levels playing a secondary role. A small number of hybrid operators combine both approaches. More and more DACCS companies use their knowledge to diversify their business model and integrate it vertically by providing a whole portfolio of services – both upstream and downstream (based on interviews with DACCS experts). This includes taking on MRV (Measurement, Reporting and Verification) as a core business area and offering portfolio management that provides customers with a diversified range of CMA certificates. Climeworks, for instance, has evolved from a pure technology provider toward a broader climate solutions positioning, and now reports a portfolio of five projects, 40 new clients, and approximately 450,000 t of CDR sold – reflecting a deliberate strategic broadening beyond CDR delivery alone.

Given these structural constraints, viable DACCS business models within Switzerland are therefore limited to roles that do not require domestic scaling of capture or storage infrastructure: **technology and component supply, licensing of proprietary processes and patents, as well as participation in voluntary carbon markets through the development of MRV methodologies, certification standards, and the broader CDR ecosystem** – areas where Swiss companies such as Climeworks are already internationally active.

2.5.13 Main conclusions and future research

Timing: DAC has moved from pilot to early commercial scale within the DeCIRRA project period. Climeworks' Mammoth plant (36 kt CO_2/year) has been operating since 2024, 1PointFive's STRATOS facility (500 kt CO_2/year) entered final commissioning with Phase 1 startup targeted for Q2 2026. The direction of travel is nevertheless not simply upward: Climeworks has pivoted from a scale-first to a learn-first strategy, cut around 22 % of its workforce in 2025, paused its planned US expansion, and now aims to demonstrate cost reduction at smaller scale rather than build ever-larger plants. DAC is therefore best characterised as technologically demonstrated but commercially pre-viable: a technology in an iteration phase rather than a deployment phase.

Potential: Globally, DAC is expected to reach only about 0.55 Mt CO_2/year in 2030 on the basis of installations operating or under construction, against announced project pipelines approaching 65 Mt CO_2/year by 2030, a gap that illustrates how little of the announced capacity should be treated as firm (see also Section 3.4). For Switzerland the assessment is clearer and more restrictive: DAC is not deployed domestically in any scenario, for economic reasons and because of limited domestic geological storage. DAC is therefore unlikely to be deployed in Switzerland itself; the country's role will lie primarily in supplying the technology and participation in DAC projects abroad, not domestic capture at scale.

Energy and waste heat need: LCA studies consistently identify the GHG intensity of the heat and electricity supplied to the process as the decisive determinant of whether DACCS delivers effective removal at all. This is the same allocation conflict identified for BECCS at waste-incineration plants, and it should be treated as one question rather than two: future research should quantify, for a given quantity of low-grade heat, whether it delivers more climate benefit in DAC regeneration, in a district heating network displacing fossil heat, or in enabling capture at an existing point source. Answering this requires more geographically and seasonally disaggregated modelling, since Switzerland's constraint is the heat and electricity in winter, not the equipment.

Costs: DAC remains the most capital-intensive engineered CDR pathway, with a net carbon efficiency of only 55–80 % against 85–100 % for BECCS and 90–100 % for biochar. First-of-a-kind costs are estimated at US$ 400–1000+/tCO_2 (or US$ 350–550 with lowest-cost renewables), falling under favourable conditions under ambitious assumptions about renewable costs, capacity factors and energy efficiency. The DeCIRRA DAC Calculator case studies have shown how far current projects are from viability and that CO_2 prices needed to reach US$ 350-530 per tCO_2. Capital expenditure accounts for 55–60 % of levelized costs. Since certificate-based business models require such high CO_2 prices which are far from current ETS prices, DAC is currently sustained by a narrow set of buyers paying premium

prices rather than by cost competitiveness. Future research should ensure that learning curves and net removal claims should be built on measured capacity factors and measured recovery losses, not on nameplate capacity.

Innovation: The highest-leverage research need is material innovation. Sorbent working capacity at ~400 ppm, regeneration energy (currently 4–10 GJ/tCO_2), cycle kinetics, water co-adsorption and long-term stability (>1,000–5,000 cycles) jointly determine plant sizing, energy intensity, replacement frequency and both CAPEX and OPEX; sensitivity analyses indicate that targeted improvements in these parameters could reduce levelized costs. However, Jia and Kirk (2026) attribute this to the entropy-of-mixing penalty of capturing a 0.04 % gas, i.e. a physical rather than engineering limit that material innovation in advances in sorbent materials cannot remove.

Accounting: DAC has not yet a natural home in national inventories. The IPCC Task Force mandate to deliver a methodology report on CDR, CCS and CCU by the end of 2027 is therefore as consequential for DAC as for BECCS. On the project side, the methodology landscape has matured considerably and is beginning to converge: the CCS+ DAC module (VMD0056) operates alongside Verra's general CCS methodology, Absolute Climate finalised a DACS methodology in 2025, Puro.earth integrated the CCS+ BECCS and DACCS framework into its own certification in October 2025, and the first CRCF delegated regulation of February 2026 includes a DACCS methodology. The remaining gap is Article 6.4, where removals standards were adopted in October 2024 but no DACCS methodology had been adopted as of mid-2026. Climeworks' pilot bilateral transaction under Article 6.2 is a useful precedent, but the rules under which such transfers are recognised, and how the removal is attributed between capturing and storing country, remain unsettled.

Durability/Permanence: With geological storage, DAC offers the highest durability of the CMAs examined, and permanence is not the principal open question. Attention should instead focus on the difference between gross capture and net removal: energy-related emissions, CO_2 recovery losses, and construction and maintenance of the DAC unit and the transport and injection infrastructure all reduce the removal achieved, and long-term reservoir monitoring must confirm negligible leakage. Certification should require measured net removal per certificate rather than derived estimates.

Policies: Switzerland does not incentivise DAC in a systematic, technology-specific way. The Climate and Innovation Act provides some innovation funding and the federal government continues to support DAC research through R&D grants and pilot support. This is almost entirely supply-push, and supply-side support alone will not deliver the scaling DAC requires. The most important development is therefore how the federal administration is to meet its own 2040 net-zero target, under which FOEN would purchase removals. If implemented, this would create the first genuine public demand for durable removals in Switzerland, and its design deserves close attention: procurement volumes, quality criteria, and the balance between domestic and imported removals will have an impact if DAC will be part of it. Internationally, the comparators are the US 45Q credit and the UK's GGR business model offering 15-year contract-for-difference revenue support – both demand-side instruments. Future research should assess which demand-side design is transferable to the Swiss context.

Co-benefits: DAC's principal structural advantage is that it competes for neither land nor biomass, which distinguishes it from every other CMA examined here and makes it complementary rather than substitutive. Siting flexibility allows co-location with low-carbon energy and storage, avoiding long-distance CO_2 transport where capture occurs at the sequestration site. Captured CO_2 can serve CCU applications – synthetic fuels, chemicals, building materials – providing a non-fossil carbon feedstock, and the requirement for low-carbon power creates demand that can support renewable deployment.

Risks: The dominant risk is that costs do not fall as projected, leaving DAC dependent on a small number of premium buyers and on public funding. This concentration makes the global DAC market acutely sensitive to single-jurisdiction policy shifts, as the 2025–2026 turbulence around the US Regional DAC Hubs demonstrated. Further risks include the environmental footprint of construction, water consumption and sorbent chemicals; energy demand that, if not met from low-carbon sources, erodes or eliminates the removal; competition for the same low-grade waste heat needed elsewhere in the energy system; and reputational risk to the wider CDR field if announced capacity continues to exceed delivered capacity by two orders of magnitude.

2.6 CO_2 transport and storage

2.6.1 General description

Transport

Transportation of CO_2 can be done by truck, train, barge on the river, ship on the ocean and pipeline. There have been detailed studies on the transportation costs for those different modes under the DemoUpCarma[41] project. For quantities from above prox. 1 Mt CO_2/year, transport via pipeline is considered the most cost effective (Becattini et al. 2022) and has been the focus in the DeCIRRA project. In Switzerland there is a potential of approx. 7 Mt CO_2/year from hard to abate CO_2 emissions (e.g. waste incineration, cement production).

Multi-modal transport (meaning starting with a truck, changing to train or ship) with hubs seems to be too expensive and is therefore not very likely to happen. However, rail transportation to the North Sea may well be an option for smaller emitters without connection to a pipeline. Presently there is no regulation on CO_2 pipelines for the quantities in place in Switzerland. In general, the cantons are responsible for creating an according act because CO_2 is presently considered as waste. However, regulations for CO_2 pipelines in Switzerland are under preparation and the Swiss Federal Council plans to accelerate the expansion of carbon capture and storage (CCS) through a new framework law that harmonises rules for building the necessary CO_2 pipelines and underground storage facilities. This implements Motion 24.4256 on a national regulation for CO_2 capture, transport, and storage. The consultation of this regulation is foreseen in Q3/Q4 2026. Complementary measures in the new CO_2 Act (2030) will increase investment security, for example through targeted financial support.

Currently there are very few CO_2 operational pipelines, mostly in the US or Canada. In the US there are around 7000 km of CO_2 pipelines mostly related to enhanced oil recovery. The Sleipner gas field in Norway, Europe's biggest geological storage facility, under the name of "Northern Lights", relies exclusively on ship transport. A pipeline from the Netherlands and/or Belgium is being planned.

Several companies are active in the field of CO_2 transportation by pipeline in Switzerland. On the one hand, there are regional gas companies that built, operate and maintain the regional high pressure gas grids in Switzerland. They are mainly owned by cities and municipalities. The routes of their pipeline systems form a good foundation for the future routing of a CO_2 pipeline system. Together with other relevant stakeholders, they are preparing to launch an initiative in Q3 2026 to foster the development of CO_2 pipelines.

On the other hand, there is a small company called CO_2 Pipeline Schweiz AG (CPS)[42] that was founded in 2025 and sees itself as a developer of a Swiss CO_2 pipeline and logistics system. They are working on a pre-FEED-study which is financed by the Swiss government and several cantons. The company intends to establish a FEED study after the pre-study for a Swiss CO_2 pipeline. The first section is planned to run between Basel and Zurich, with the network to be expanded in further stages thereafter (see Figure 38). In addition to emitters along the Basel–Zurich corridor, those in the eastern catchment area of the pipeline are also planned to be included with other transport options to optimally plan the route, capacities and local connections. Identifying a viable route for the CO_2 pipeline requires balancing a range of technical, environmental, and economic constraints. Key restrictions include safety setbacks, proximity to buildings, sensitive water bodies, and protected nature reserves – areas where routing is either prohibited or subject to strict conditions. To ensure alignment with spatial planning requirements, the relevant cantonal authorities have been contacted regarding land-use planning. Their input is essential for identifying permissible corridors early and avoiding conflicts with existing or planned land designations. However, some violations of routing criteria are likely unavoidable, as trade-offs between economic feasibility and full compliance will need to be made. The regional gas companies and the CPS are in discussion for closer cooperation.

[41] http://www.demoupcarma.ethz.ch/en/home/
[42] https://www.co2pipeline.ch/

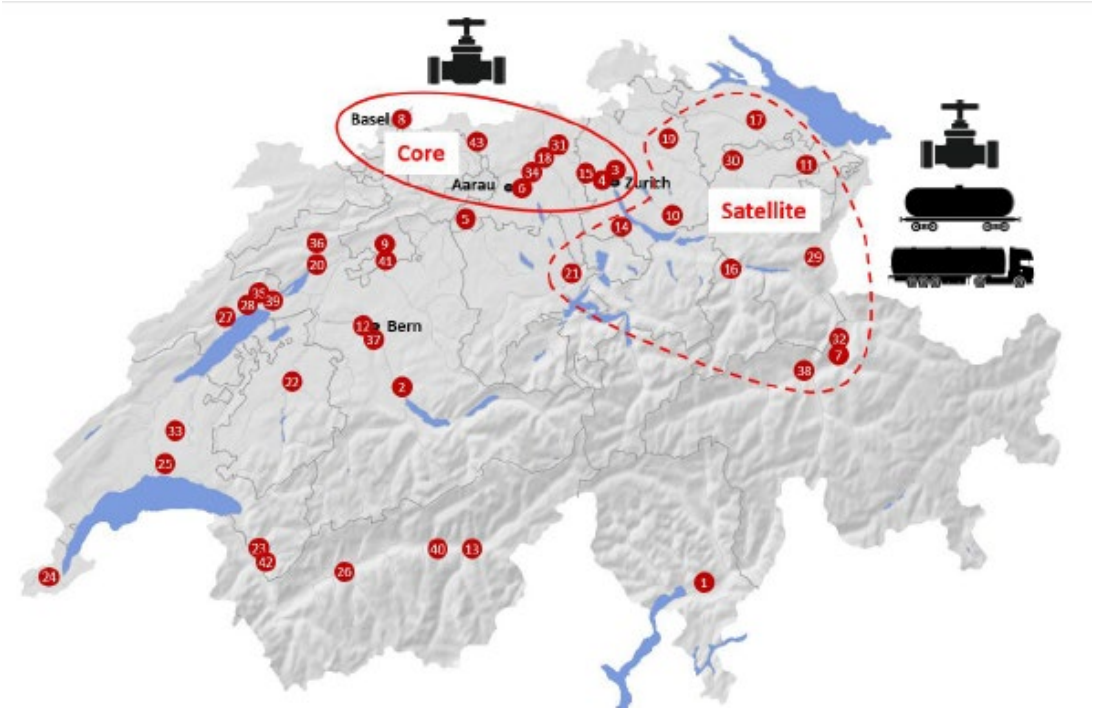


Figure 38: Swiss point sources (in red) and expected transport modes investigated by CO_2 Pipeline Schweiz AG (Presentation at CDR Platform meeting, June 2026).

Equally important is how Swiss CO_2 pipelines can be connected to networks in neighbouring countries (Germany, France and Italy), since domestic storage will not be available in the near term and its eventual capacity is likely to be insufficient.

Connection to France via Karlsruhe: A key opportunity lies in the existing oil pipeline infrastructure running from Marseille to Karlsruhe, much of which is no longer in active use and is therefore available for repurposing. Between Marseille and Lyon, a dedicated EU funded "Rhône CO_2" project managed by SPSE is already underway to convert this infrastructure for CO_2 transport, providing a concrete foundation to build on. This north–south corridor offers some flexibility in terms of routing and phasing, with only an estimated 40 km of new pipeline missing to complete the connection. From Marseille (Fos-Marseille port) the CO_2 would need to be shipped to the Italian storage site Ravenna. There is already a project, Callisto,[43] which plans to organise this shipping part.

Connection to Belgium and Netherlands via Karlsruhe (see Figure 39): from Karlsruhe the network could also connect onward to pipelines linking to Belgium and the Netherlands, opening access to established CO_2 storage hubs in the North Sea. The German transmission system operator Open Grid Europe (OGE) has furthermore indicated in its strategy that it plans to integrate Swiss CO_2 into its network, reinforcing the viability of this cross-border approach.

Other options which are not pursued by the CO_2 pipeline Schweiz AG would offer CO_2 transport to Germany or for the Rhône Valley region of Switzerland to Italy.

Connection to Germany: In Germany, Open Grid Europe (OGE, the biggest Transport System Operator (TSO) in Germany) intends to develop a German-wide CO_2 pipeline network to connect the emitters with ports in the Netherlands. Belgium and Danmark. Their routing is mainly along the existing gas pipeline system. It is presently foreseen that there could be a connection to Switzerland at the existing interconnection point of the gas pipeline in the region of Wallbach.

Connecting to Italy: One option for Switzerland would be repurposing the old oil pipeline (E50), unused since 2015, which is located at the old Tamoil refinery in Collombey (Monthey, Valais canton) and ends in San Nazzaro (Italy) at the refinery. Without additional modification, the existing pipeline capacity is 400-500 kt CO_2/year. With extension (additional compression station and doubling of the pipeline) it can reach 2.5 Mt CO_2/year. As there is little experience in retrofitting pipelines, this may be challenging. An additional pipeline would be necessary to reach a potential storage site in Ravenna and until now, the

[43] https://www.callisto-pci.com

general understanding is that Italy does not want to import CO_2 from Switzerland so that more discussion on the governmental level would be necessary. If the CO_2 would need to be shipped into another country, there is no CO_2 terminal in Genoa, and only the portion to Ferrera is unused, requiring a new pipeline for the last 25% to Genoa. Within Switzerland, Collombey is far from the main emitters (cement plants and waste incinerators), requiring additional pipelines (Nick and Thalmann 2021).

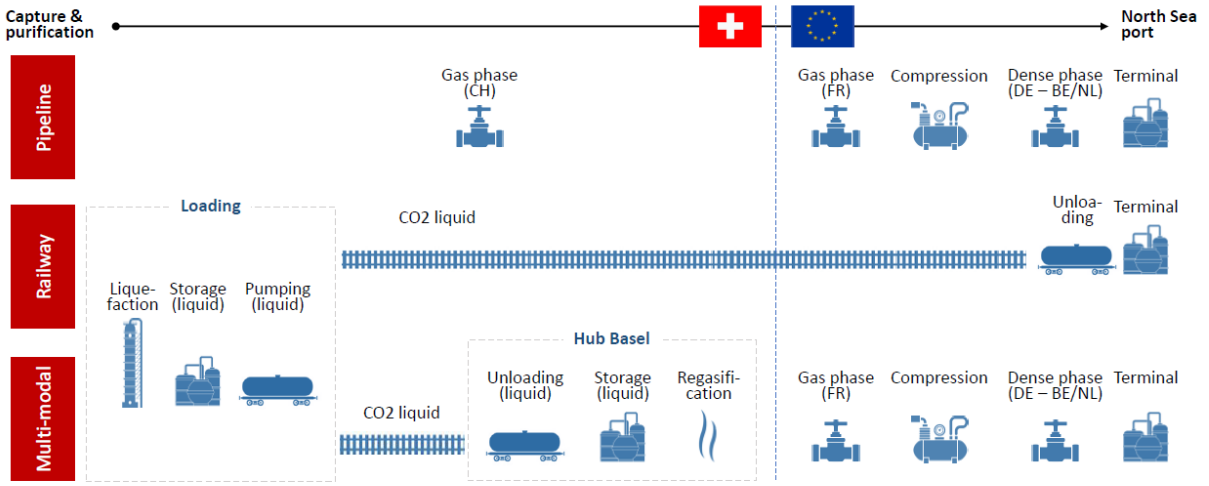


Figure 39: Transport chain archetypes presented by CO_2 Pipeline Schweiz AG (Presentation at CDR Platform meeting, June 2026).

Storage

Many of the technical NET approaches described above, such as BECC and DACC, will only lead to negative emissions if the captured or filtered CO_2 can be permanently stored. Investments in these technologies therefore depend to a large extent on whether the final link in the value chain, the storage of CO_2, is secured.

According to the IPCC (2005), there are six different geological storage options (see Figure 40), at different depths, most of which are available both on land and under water:

1. disused gas and oil fields
2. utilisation to further exploit natural gas or oil fields
3. deep, unutilised salt pans with water-saturated reservoir rock
4. deep, non-exploitable coal seams
5. utilisation of CO_2 for methane recovery from coal seams
6. other reservoir rocks such as basalt, oil shale and other cavities.

Information on CO_2 storage sites in Switzerland is based on information from geothermal drilling or on the NAGRA nuclear waste repository. Switzerland only has one disused natural gas field (Finsterwald, Entlebuch) and no oil fields, and the coal seams are not utilised for financial reasons. This leaves the third and sixth storage options, i.e., storage in saline aquifers and the utilisation of other storage rock. According to a study by Driesner et al. (2021), there is a potential CO_2 storage site in Treycovagnes, near the Holcim cement plant (Eclépens site).

Due to the chemical properties of CO_2 (the density is strongly dependent on temperature and pressure), storage only makes sense from around 800 metres underground, as the volume decreases sharply at such depth and significantly more CO_2 can be stored (presentation by Christophe Nussbaum from swisstopo in Disentis).

According to swisstopo, 7 combinations of possible reservoir rock with overlying (dense) cap rock are available in the Swiss Plateau:

1. Upper Marine Molasse (OMM) sandstones / Upper Freshwater Molasse (OSM) marl
2. Upper Malm - Lower Cretaceous limestone / Lower Freshwater Molasse (USM) marl
3. Mainrogenic limestone / Effingen Member limestone marl
4. Keuper sandstone, Arietenkalk limestone / Lias, Opalinus clay
5. Upper shell limestone / gypsum Keuper evaporites

6. Red sandstone and fractured crystalline (non-sedimentary) basement / anhydrite group evaporites
7. Permo-carboniferous trough sandstones / permian shales or anhydrite group evaporites.

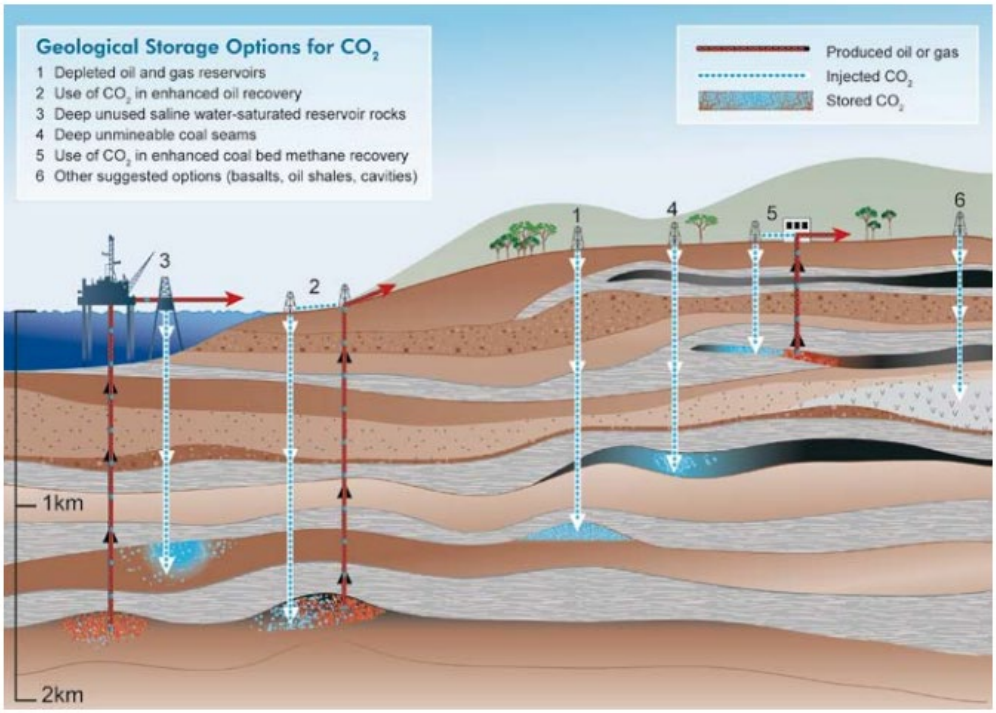


Figure 40: Options for storing CO_2 in geological formations (Intergovernmental Panel on Climate Change (IPCC) 2005).

2.6.2 System boundaries, material and emissions flows, and main drivers

The system boundaries for the quantification of GHG emissions and other environmental impacts associated with the transport of CO_2, e.g. between point sources where CO_2 is captured to the geological storage sites, include the construction/production of the infrastructure for transport (e.g. pipelines, trucks), the operation of the transport infrastructure with emissions due to e.g. CO_2 leakage and fuel combustion and GHG emissions due to land use change, and the end-of-life treatment of the infrastructure with its associated impacts.

System boundaries for quantifying GHG emissions and other environmental burdens associated with geological storage of carbon dioxide include the infrastructure at the injection site above and below ground, the energy supply for CO_2 injection, potential monitoring systems and, if applicable, short- and long-term CO_2 emissions during the storage process.

For other types of storage see the sections on biochar or TCCS.

2.6.3 Co-benefits

There are no environmental co-benefits from the transportation of CO_2.

The only currently known co-benefit of CO_2 storage is the possibility of being able to further exploit existing natural gas or oil fields with the CO_2, as the injection creates additional pressure and pushes out gas and oil that could not be extracted before. This effect is counterproductive in terms of climate protection. However, in some circumstances, it can additionally finance the capture and possibly lead to a lower rate of equity (ROE) and thus contribute to the fossil raw materials being produced with lower energy consumption. This can, for example, make the extraction of very energy-intensive, environmentally harmful oil shale sands unprofitable.

2.6.4 Risks

There are many risks associated with building a CO_2 pipeline and storing CO_2 (see Table 8). In addition to regulatory risks, there are organisational/political risks including the risk of missed connection and delays of other countries in building their CO_2 infrastructure which Switzerland will depend on (e.g., Germany, Italy, France). There are risks for the environment, for example, that the drinking water is contaminated if there are any leakages. There may also be economic risk as it must be decided who pays for the part of the CO_2 pipeline which is purely needed for the connection to the other country. If this is not resolved, there is a risk of a stranded asset.

Table 8: Overview of risks for CO_2 infrastructure (transport and storage).

Risk Category (Lead)	Start-up Phase	Operating Phase
Regulatory Risks	- Authorization procedures - Spatial planning - Technical standards	- Maintenance regulations - Infrastructure monitoring requirements
Organisational / Political Risks	- Coordination between federal, cantonal, and private actors	- International partners refusing CO_2 transportation and storage
Environmental Risks	- Environmental impact assessments e.g. groundwater interference - Seismic activity in storage exploration	- CO_2 leakage incidents and rupture e.g. due to corrosion - Seismic activity in feeding the storage
Economic Risks	- Investment risks: lock-in, stranded assets - Cost overruns	- Long-term commitment (15-20 years) - CO_2 price and volume uncertainty - Market power - Lack of suitable Swiss geological storage
Safety / Health Risks	- Insurance	- Liability management for CO_2 leakage - Emergency response
Technical Risks	- Construction delays	- Undersized pipeline design
Social Risks	- Public acceptance of construction sites	- Public acceptance of infrastructure - Media influence and storytelling - Public hearing outcomes

Transport

Within the DeCIRRA project we have focused particularly on public risks, namely the perception of the CO_2 transport options by the Swiss population (see Section 1.6 for methodology), as this may be a major risk for investors and no information was available for Switzerland.

Our results show that across all six transport options investigated, around half of those surveyed support the option assigned to them. A further 38% of respondents are neutral (Figure 41). Overall, only 11.94% of respondents reject the CO_2 transport route presented. A closer look at this group reveals a consistent pattern: those with a negative attitude tend to be older and express less concern about climate change. Furthermore, whilst they objectively possess less knowledge about climate-friendly behaviour, they overestimate their own level of knowledge. Furthermore, they feel less personally responsible for contributing to the fight against climate change and have less trust in both the government's climate policy and the assessments of climate researchers. Notably, socio-demographic factors such as gender, canton, household size and income do not play a statistically significant role in shaping a negative attitude.

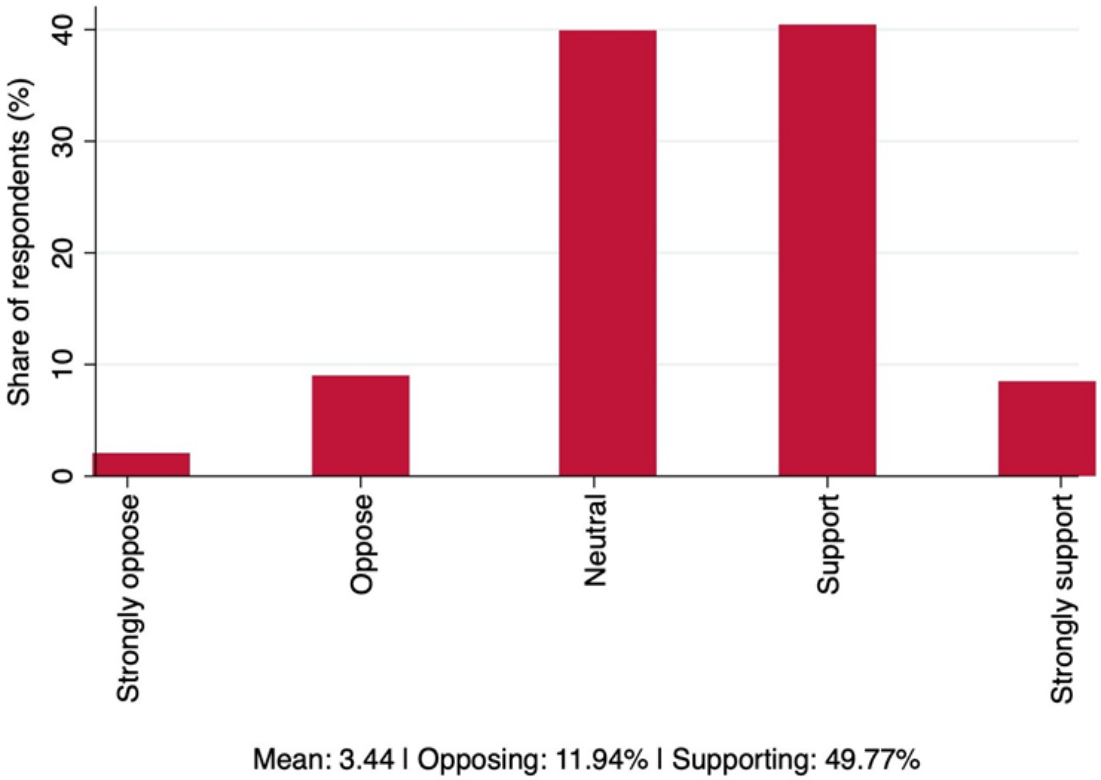


Figure 41: Frequency across all six transport options: ‘’To what extent do you support this potential transport route to a permanent CO_2 storage site?”

A comparison of the six transport scenarios reveals clear differences in public support (Figure 42). Pipeline solutions receive the highest level of approval overall, with the repurposing of an existing pipeline being rated significantly higher than the construction of a new underground pipeline (t=2.4653). When it comes to above ground transport, the train is slightly preferred (but not significantly) over the electric lorry (t=1.4875). Overall, pipeline transport performs significantly better than transport by rail or truck (t=3.9277). Interestingly, the additional information on hazardous goods and safety standards for rail and truck transport has no influence on support (t=0.0287 and t=0.2856). In contrast, information on existing CO_2 transport in Switzerland for industrial purposes significantly increases average approval across all scenarios (t=–3.8697). Higher education and higher income are positively associated with support, while suburban residents and those living farther from a railway station show significantly lower support. Finally, we find that respondents significantly underrate the support of others for the transport compared to their own support (see Boogen et al. 2026).

This study offers actionable insights for the communication and planning of CCTS infrastructure in Switzerland. Our findings suggest that leveraging existing pipeline networks should be prioritised where feasible, as repurposing of existing infrastructure appears to ease public acceptance. Beyond infrastructure choices, communication strategies matter: there is a need to more actively highlight that CO_2 transport already takes place in Switzerland and that public opposition is generally low. The latter may help correct the systematic misperception that individuals underestimate others' support for CO_2 transport options and thus could help to increase social acceptance further.

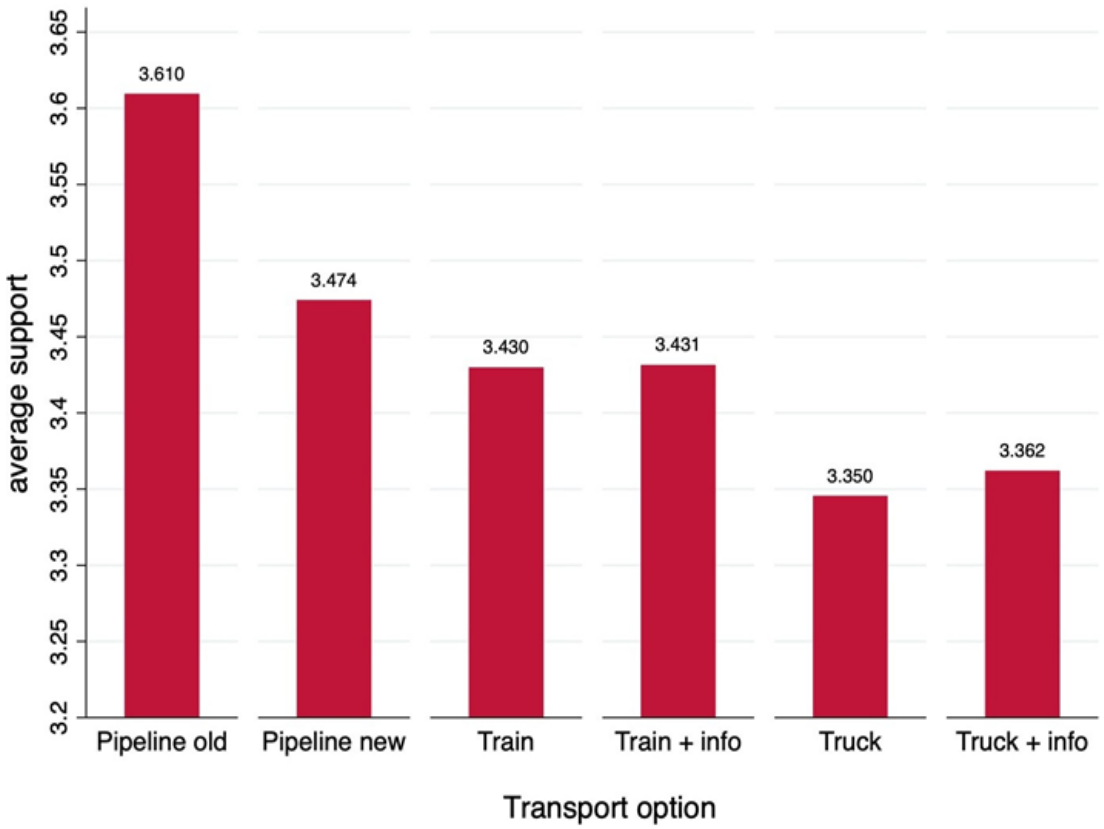


Figure 42: Frequency of assessment of a single transport option: ''To what extent do you support this potential transport route to a permanent CO_2 storage site?"

Storage

According to Christophe Nussbaum from swisstopo, the main risks of CO_2 storage are as follows (see also Figure 43), whereby a distinction must be made between gradual and abrupt leaks:

- Leakages in the CO_2 reservoir or during injection, through which CO_2 can escape back into the atmosphere,
- Groundwater is contaminated by a CO_2 leak,
- Seismic risk (for earthquakes), due to CO_2 injection into the reservoir.

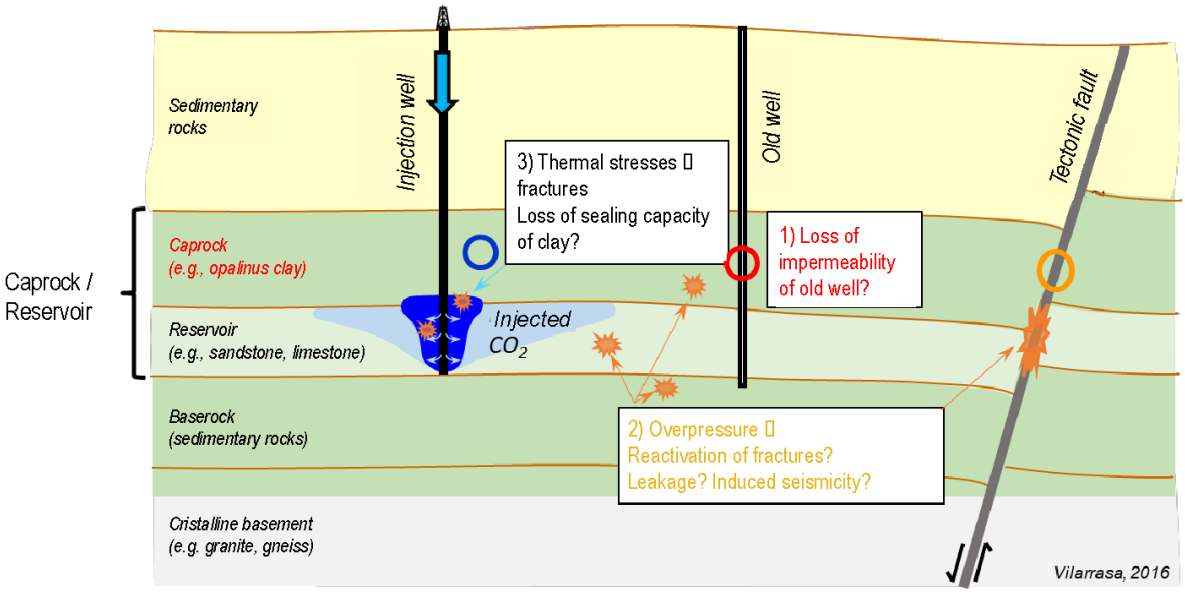


Figure 43: Potential causes of induced microseismicity and seismicity related to geological carbon storage (Vilarrasa 2016).

Lack of safety of CO_2 storage sites could pose a risk to the infrastructure and buildings above them, but also to nature.

As there is no experience to date over very long periods of time (the Sleipner project in Norway was launched in 1996), the long-term risk cannot yet be estimated accurately.

A further risk is that, under the current legal framework, the cantons have sovereignty over underground matters (see Section 2.6.8). There is therefore a risk that no agreement can be reached between the federal government and the cantons and that problems may also arise due to restrictions on the rights of private landowners.

There is a risk of high demand for storage capacities abroad, which would lead to high prices with limited supply. As the necessary infrastructure investments also increase dependency, it would make strategic sense to develop national storage facilities in addition to foreign storage capacities, as this would strengthen the negotiating position and provide an alternative for storage in the event of pipeline maintenance or other problems (discussion at workshop).

And finally, there is a risk of **non-acceptance by the population**, whereby it can be assumed that acceptance of offshore storage is higher than of storage on land, especially if this is populated. While Switzerland does not have any offshore storage sites, other aggregate states for storage – in addition to storing CO_2 as a gas – exist, which we have further explored in the DeCIRRA project.

We asked in our representative survey (see Section 1.6) “What are Swiss citizens' intuitive levels of comfort with different permanent carbon storage methods, and how does solid carbon storage compare with geological CO_2 injection?”

Research on public perceptions of CDR consistently shows that acceptance is method-specific and strongly influenced by information framing, familiarity, and perceived naturalness. Geological CO_2 storage and cross-border transport tend to be less supported than land-based or biological methods (Shrum et al. 2020; Anders et al. 2024). Studies from Germany, Austria, and the UK find that the notion of "tampering with nature" is a recurrent concern for engineered CDR, and that trust in governing actors and early engagement are critical for public acceptance (Böhm et al. 2021). A German vignette study finds that respondents strongly prefer domestic CDR programmes over offsets abroad, and that afforestation attracts more support than direct air capture, with biodiversity impacts and renewable energy use mattering more than storage permanence (Merk et al. 2023). This preference structure has direct implications for the framing of CO_2 storage. A recent cross-national study drawing on focus groups across 22 countries finds that publics across the global North and South share concerns about land-use trade-offs and prefer governance mechanisms that emphasise systemic coordination and regulation of industry over incentivising innovation alone (Low et al. 2024).

There are only a few representative Swiss surveys on public acceptance / support of different NET, but none includes different types of storage. The Swiss Environmental Panel (Nov 2023 - Feb 2024) showed that the knowledge about CDR is very limited and the overall public support for the use of CDR alongside mitigation to reach net-zero by 2050 appears very weak (Rhein et al. 2025). A second study focussed on two specific CCT(U)S pathways, including CO_2 storage in recycled concrete in Switzerland and geological storage in Iceland (Dallo et al. 2024). They showed that the acceptance and support are higher for the Swiss CCT(U)S pathway than the Icelandic pathway.

We focus on Swiss storage options only. Results from our representative survey reveal a clear and policy-relevant pattern in Swiss citizens’ intuitive comfort with different permanent carbon storage methods (Figure 44).

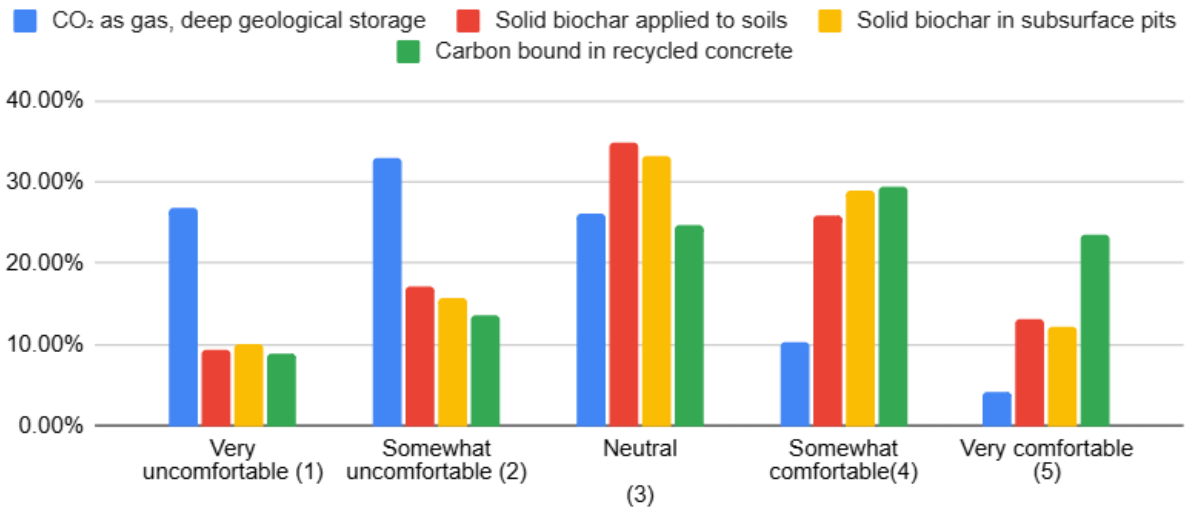


Figure 44: Level of comfort with permanent carbon storage methods among Swiss citizens.

Note: Combined discomfort (responses 1+2) and comfort (responses 4+5) are calculated as: CO_2 as gas, deep geological storage: 59.9% uncomfortable, 14.5% comfortable; Solid biochar applied to soils: 26.5% uncomfortable, 39.0% comfortable; Solid biochar in subsurface pits: 26.0% uncomfortable, 41.2% comfortable; Carbon bound in recycled concrete: 22.5% uncomfortable, 53.1% comfortable.

Geological CO_2 injection is the least accepted method by a wide margin: 59.9% of respondents reported feeling uncomfortable (responses 1 or 2), while only 14.5% felt comfortable (responses 4 or 5). The solid carbon options present a strikingly different picture. Subsurface storage of solid biochar, the option most conceptually analogous to hydrochar storage in disused pits, was viewed positively by 41.2% of respondents, with only 26.0% reporting discomfort. Biochar applied to soils achieved a similar profile (39.0% comfortable, 26.5% uncomfortable). Carbon bound in recycled concrete garnered the highest overall comfort ratings (53.1% comfortable, 22.5% uncomfortable), likely reflecting the more familiar and utilitarian framing of concrete reuse.

The contrast between geological CO_2 storage and solid biochar storage in subsurface pits is particularly notable: the two options involve broadly comparable permanence and depth of intervention yet differ by nearly 34 percentage points in the combined values (59.9% vs. 26.0%). This difference cannot be attributed to permanence or geological intrusiveness alone; it more plausibly reflects the perceived naturalness of solid carbon (familiar from charcoal and coal) versus compressed gas injection, a theme consistent with findings from European CDR acceptance studies (Shrum et al. 2020). Psychological research has long established that invisible and intangible hazards like gases are perceived as riskier than visible, solid ones, as they score higher on Slovic's 'unknown risk' dimension (Slovic 1987).

The general disposition toward domestic storage is strongly positive. When asked whether CO_2 storage should take place in Switzerland if it can be done safely, 73.4% of respondents agreed (29.0% "definitely yes", 44.4% "probably yes"), with only 16.5% opposed (11.5% "probably not", 5.0% "definitely not") and 10.1% uncertain. This conditional majority support is a crucial governance finding: it suggests that public resistance to domestic storage is not a structural barrier but rather depends on how – not whether – storage takes place. This pattern of moderate but not absent public support is consistent with earlier Swiss survey evidence on NETs more broadly (Wenger et al. 2021), while our findings add method-specific differentiation that the earlier study did not address.

Self-assessed knowledge of CO_2 storage technologies is low across the population. Nearly half of respondents (47.3%) reported knowing nothing or very little about CO_2 capture and storage technologies (14.8% "I know nothing about it"; 32.5% "I know very little"). A further 38.6% reported knowing "a little", while only 14.2% reported knowing "quite a bit" or "a lot". This low baseline knowledge, combined with broadly positive intuitive support of solid carbon storage, suggests that informed deliberation is unlikely to reduce –and may well increase – support for hydrochar-type storage options, particularly if communication emphasises the familiar, solid, and natural character of the material.

The survey results provide an important corrective to the assumption that public opposition is the primary barrier to deployment. For solid carbon storage in subsurface locations, Swiss-German citizens are substantially more comfortable than with geological CO_2 injection. With 41% expressing comfort with subsurface solid storage against only 14% for deep gas injection, the perception differential is large and

unlikely to reflect merely superficial framing effects. It appears to reflect a deeper intuition, consistent with findings from other European countries (Shrum et al. 2020), that solid and familiar-seeming materials are less threatening than compressed gas forced into geological formations.

This public acceptance profile is a governance asset that has not yet been mobilised in Swiss CDR policy. Our expert interviews show that stakeholders are genuinely uncertain about how the public views different storage options, yet the answer, at least at the level of intuitive response, is already available. Making this evidence visible in policy discussions could shift the framing of hydrochar storage from a regulatory obstacle to a socially preferred alternative to geological CO_2 storage. It could also counterbalance the moral hazard concern raised by several interviewees: that CDR risks reducing mitigation ambition. This concern is termed mitigation deterrence in the academic literature and refers to the risk that the availability of CDR reduces pressure for near-term emissions cuts (Carton et al. 2023). Evidence suggests this risk depends strongly on governance context and is not inevitable (Hart et al. 2022; Brad et al. 2023). Demonstrating that a cost-effective, publicly supported, domestically implementable CDR option exists strengthens rather than weakens the case for a credible Swiss net-zero strategy.

2.6.5 Estimates of costs, potentials, and main drivers

Transport

SAIPEM undertook a conceptual planning study for a CO_2 pipeline in Switzerland contracted by the VBSA in 2020 (SAIPEM 2020). The study focused on a collection CO_2 Pipeline for 32 larger Swiss CO_2 emitters and does not include any transmission volume. The suggested pipeline was planned to have a total length of 1032 km with two main trunklines (east and west) and would closely follow the existing natural gas pipeline corridor (see Figure 45). It differentiated between gas (Maximum Operating Pressure = MOP = 35 barg) and dense phase (MOP = 145 barg).

The Capital Investment Cost (CAPEX) and Operating & Maintenance Costs (OPEX) were estimated for the pipeline including the necessary compression units and the energy to run those (see Table 9). The CAPEX required is estimated between EUR 2.8 and 3.2 billion and the operating costs are approximately EUR 200 million per year. In relation to the quantities expected to be produced and transported, this corresponds to about 35 EUR/tCO_2.

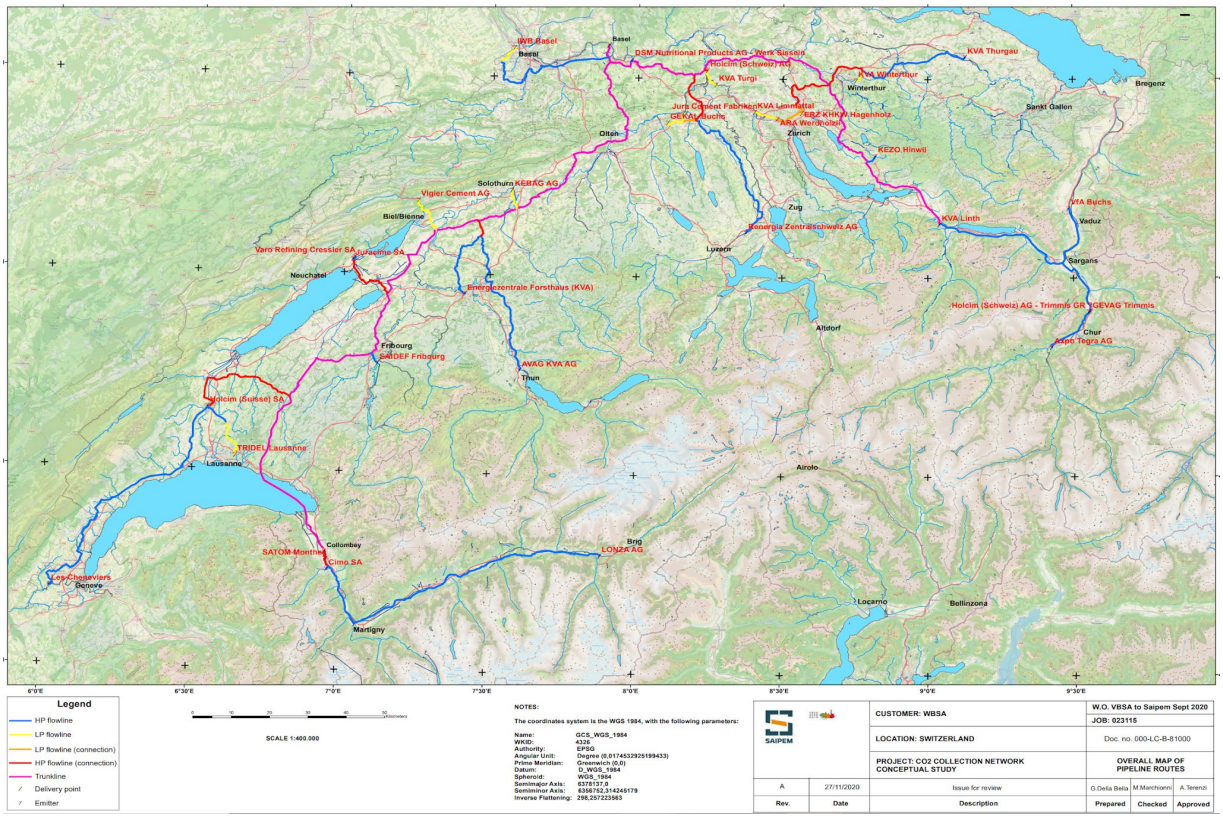


Figure 45: CO_2-Network Map (SAIPEM 2020).

Table 9: CO_2 pipeline study estimates (SAIPEM 2020).

Euro	Gas (MOP = 35 barg)		Total	Dense (MOP = 145 barg)		Total
	Pipeline	Compression units		Pipeline	Compression units	
CAPEX	1.8	0.9 + 0.4	3.2 billion	1.2	1.5 + 0.08	2.8 billion
OPEX	26.5	113 + 59	199 million	18.5	175 + 5	199 million

According to a study carried out by BAK economic intelligence in cooperation with DENA on behalf of the FOEN (Albicker et al. 2023), the total costs of the CCS system amount to CHF 16.3 billion, whereby the costs of capture dominate at 56%, and the transport costs associated with the infrastructure investments by pipeline in Switzerland only account for 30%. The range of estimated total costs is between CHF 11.2 and 21.4 billion. The fact that the capture costs are estimated to be significantly higher than the transport costs is new compared to most modelling assumptions. Per tonne of CO_2 avoidance (capture and transport), the base scenario estimates 180 CHF/tCO_2, which depends heavily on how quickly the pipeline is built and how much CO_2 is transported in it.

The following framework conditions may increase the cost substantially:

- Is it feasible to construct a second pipeline under existing right of way agreements?
- How and by whom is the infrastructure financed?
- Under what operating models and regulations is the pipeline built and managed?

Storage

In the 2050+ energy scenarios, the costs for pure CO_2 storage in Switzerland are estimated at CHF 40/tCO_2 in 2030, falling over time to CHF 26/tCO_2 in 2060 (see Table 10), while CHF 10/tCO_2 is specified for pure storage offshore in salt domes (Kemmler et al. 2021).

According to a literature review by Brunner and Knutti (2022), the costs for storage in saline aquifers are estimated at CHF 6-19/tCO_2 and in reactive rock layers at CHF 2-23/tCO_2, which means that the costs assumed by the energy scenarios are rather conservative.

Table 10: Costs of storing CO_2 underground (Kemmler et al. 2021, p. 34).

Storage	Type	Current costs (min EUR / tCO_2)	Current costs (max EUR / tCO_2)
Onshore	● Exploited gas and oil reservoirs, reusing drilling/wells	1	7
	● Exploited gas and oil reservoirs, without reusing drilling/wells	1	10
	● Saline aquifers	2	12
Offshore	● Exploited gas and oil reservoirs, reusing drilling/wells	2	9
	● Exploited gas and oil reservoirs, without reusing drilling/wells	3	14
	● Saline aquifers	6	20

Global potential

There are over 10,000 Gt CO_2 of theoretical storage capacity worldwide, whereby 80% of the capacity lies in salt domes and only a small part of the theoretical potential can currently be used in practice, e.g. for technical and geological reasons, whereby this would be large enough to reach 1.5 °C in 2100 (see Table 11).

According to the Global CCS Institute (2021) after presentation by Christophe Nussbaum (Nussbaum 2023):

- 27 projects are in operation and store 36.6 Mt CO_2/year.
- 62 further projects are either under construction (n=4) or in the advanced development phase (n=58).

- A further 44 projects are in an early development phase.

If all these projects are successfully implemented, the cumulative storage potential would be around 150 Mt CO_2/year.

Table 11: Estimated geologic storage potential across underground formations globally (Gt CO_2) (Clarke et al. 2023, p. 641).

Reservoir type	Africa	Australia	Canada	China	CSA	EEU	FSU	India	MEA	Mexico	ODA	USA	WEU
Enhanced oil recovery	3	0	3	1	8	2	15	0	38	0	1	8	0
Depleted oil and gas fields	20	8	19	1	33	2	191	0	252	22	47	32	37
Enhanced coalbed methane recovery	8	30	16	16	0	2	26	8	0	0	224	90	12
Deep saline aquifers	1000	500	667	500	1000	250	1000	500	500	250	1015	1000	250

Note: CSA = Central and South America; EEU = Eastern Europe; FSU = Former Soviet Union; MEA = Middle East; ODA = Other Asia (except China and India); WEU = Western Europe

Potential in Europe

There are several storage projects in Europe. The Clean Air Task Force's tracker of CO_2 storage project capacity in Europe (Figure 46)[44] provides a good overview with an interactive map on different storage options and also provides a timeline, when capacities are becoming available.

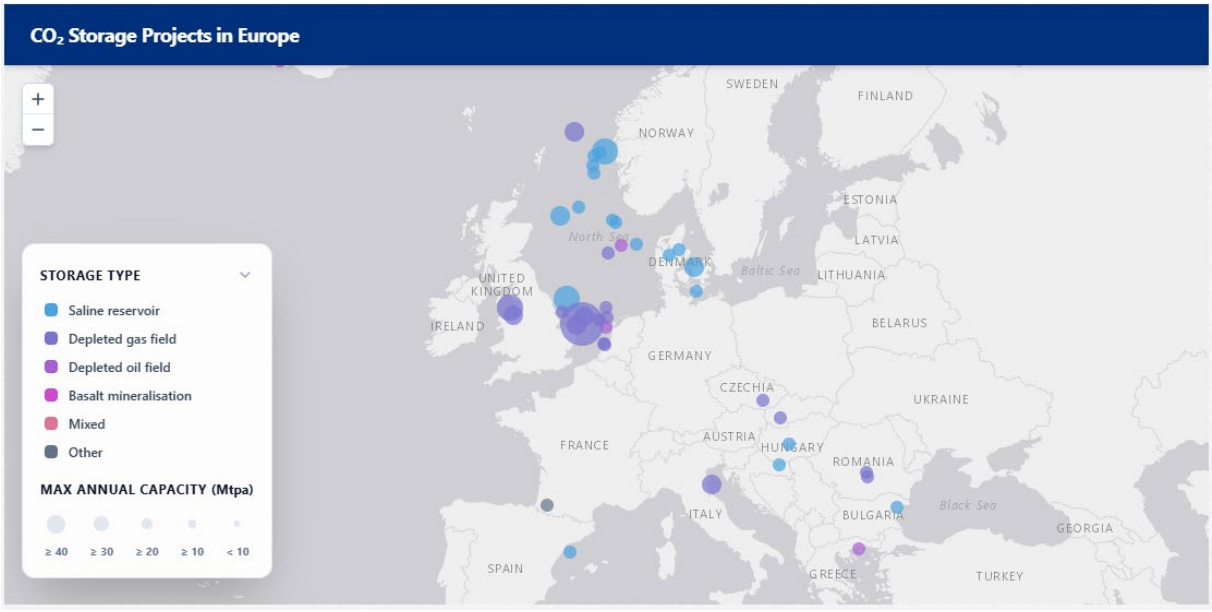


Figure 46: CO_2 storage projects in Europe (Clean Air Task Force)[41].

Potential in Switzerland

In Switzerland, there have been various studies to estimate the CO_2 storage potential, but these are still very uncertain and are being clarified following Motion 20.4063. An older, purely theoretical study (Chevalier et al. 2010) based on a literature analysis came to the conclusion that 2.68 Gt CO_2 could be stored in molasses in the Western Jura, with 0.7 Gt CO_2 in the upper Muschelkalk. A more recent study by the University of Bern shows a much lower potential for CO_2 storage in the upper Muschelkalk aquifer of only 52 Mt CO_2, between Olten and Schaffhausen (see Figure 47). According to the Energy Scenarios 2050+, 3 Mt CO_2 are to be stored domestically in 2050 (8.6 Mt CO_2 abroad), which means that the storage facility would be full after approx. 17 years if no other options are found.

Swisstopo recommends that current, more precise estimates of the storage potential under the Swiss Plateau be made using new 3D geological data from swisstopo in combination with the available physical parameters (porosity, permeability) (in particular thanks to Nagra's deep boreholes) and integration of the storage potential in fractured and karst rock.

[44] https://www.catf.us/carbon-capture/storage-project-capacity-europe/

The most recent research has refined the picture of domestic storage potential. Modelling of deep saline aquifers in the Swiss Molasse Basin and Folded Jura suggests that a representative single well could store up to 2 Mt CO_2 over a 30-year period or 0.05 Mt annually (Gunatilake et al. 2025). The study indicates that 70 to 150 similar storage sites could be found in the Swiss Molasse Basin, while about 60 wells would be needed to store the 3 Mt of unavoidable CO_2 emissions planned for domestic storage in the Energy Scenarios 2050+ (Gunatilake et al. 2025). In-situ mineralisation in suitable rock types (e.g. serpentinite) is, by contrast, constrained by complex Alpine geology, high water requirements and cost, and is not currently a viable option (Martin et al. 2025). Consistent with this, geological storage sites are not expected to be operational for at least another 15–20 years, given the subsurface exploration is still required. In the interim, the main domestic storage route is the mineralisation of CO_2 in building materials (e.g. the concrete-based storage pursued by Neustark, zirkulit and Sika under the Climate Cent Foundation programme; see BECCS section), which will have limited capacity with 0.1 Mt CO_2 storage capacity per year.

To advance the knowledge about national storage options, the pilot and demonstration project CITru (CO_2 Pilot Injection in Trüllikon), led by ETH Zurich, is investigating the feasibility of a CO_2 injection test through a decommissioned borehole in the municipality of Trüllikon (canton of Zurich). The exploration phase of CITru began in autumn 2024. It includes in-depth investigations of the local subsurface at depths of over 1,000 metres, using seismic measurements, computer simulations of various injection scenarios and CO_2 distribution at depth, and detailed risk assessments. Logistics, budget, and concession requirements for a potential CO_2 injection are also being evaluated. If the project proves sufficiently safe, environmentally acceptable, and financially viable upon completion of the exploration phase at the end of 2025, an implementation phase would be initiated – including the actual injection of CO_2 into the subsurface, which could begin at the earliest in mid-2026.

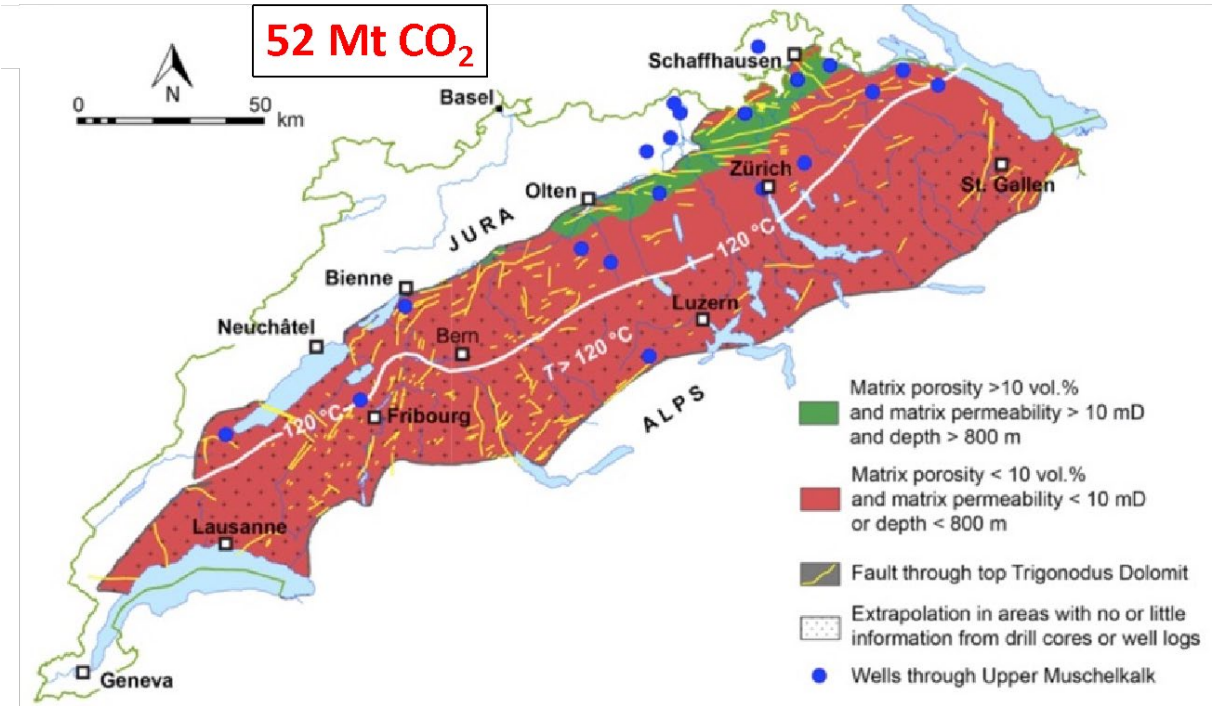


Figure 47: Potential for CO_2 storage in the Upper Muschelkalk aquifer, Switzerland (Diamond 2019).

2.6.6 The role of CO_2 transport and storage across scenarios

To enable cost-effective transport of gaseous CO_2 for storage in international partner countries, a pipeline network is required. The four scenarios assume markedly different cost levels: the Octopus and Butterfly scenarios assume CO_2 transport and storage costs of CHF 100–200/tCO_2, the Snail scenario assumes CHF 400–800/tCO_2, and the Clam scenario assumes CHF 800–1,600/tCO_2 – reflecting the

near-prohibitive costs of multi-modal transport (rail, road, and shipping) via hubs, as well as domestic storage.

The modelling results show that transport costs are the primary driver of marginal avoidance costs (see Section 4.1), and that international cooperation is essential to achieving the 2050 net-zero target, including aviation. Access to cross-border CO_2 transport infrastructure, adequate storage capacity, and expertise in CO_2 transport and sequestration are all critical prerequisites.

To illustrate the scale of what a pipeline-free approach would entail: transporting the annual volume of CO_2 captured from Swiss waste incineration plants alone – excluding cement and chemical plants – would require more than 100,000 tanker trucks per year. If lined up, these vehicles would form five continuous columns stretching the entire length of Switzerland.

2.6.7 Relevant actors

Most relevant actors were already mentioned in the Sections 2.4 on BECC or 2.5 on DACC, because transport and storage are important for all the large CO_2 emitters like waste incinerator plants, cement production plants or heating and power production plants burning wood and other fuels.

For the transport the authorities play a very important role, as they will have to adopt the regulation for permitting and operating matters and have the monitoring functions, e.g. the Federal Pipelines Inspectorate[45] (Eidgenössischer Rohrleitungsinspektorat) for technical supervision. Furthermore, there will be relevant cantonal and/or other national authorities involved. Further relevant actors are the operator(s) of the CO_2 Pipeline and their shareholder(s).

In this respect the oil industry can be an important partner, given that abandoned fossil oil pipelines may be repurposed.

Also the regional gas companies (owned mainly by cities and municipalities) with their knowledge on planning, construction, operating and maintaining of high-pressure pipelines can play an important role. The routes of their existing pipeline network could build the core of the CO_2 pipeline system. The usage of the gas high pressure pipeline for CO_2 transport is not very likely, as the gas system can also be used for renewable energy transport in gas phase and it is most likely that the system will still be in use when the CO_2 transport has already to be in place, suggesting that the CO_2 system would run parallel to the gas system.

Also the shipping, train companies like ChemOil (subsidiary of SBB) and truck/logistic industries will be very important partners, as smaller and pilot projects will rely on this kind of transport.

Internationally there are some relevant companies that plan and build pipelines in the surrounding countries, like OGE. OGE is developing a 1,000-kilometre CO_2 transport network in Germany, connecting the TES Green Energy Hub in Wilhelmshaven with several industrial sites, to which the CO_2 will be shipped and subsequently sequestered or reused for the production of e-NG. Switzerland's strategically important locations, such as Basel, can be connected to this infrastructure by train or pipelines. TES has partnered with Energie 360° and the VBSA, but it is unclear what will really be realised from this partnership, as the focus of TES is more on the Wilhelmshaven region. In addition, there are Fluxys, the Belgian gas TSO, which is very active in planning and construction of CO_2 pipelines as well as Gasunie, the Dutch TSO.

The EU foresees that the existing gas TSO shall establish the CO_2 pipeline system and maintain and operate it.

For storage, the final link in the CCS chain, the following players are particularly important in addition to all the players mentioned above, which range from emitters to regulatory authorities:

The Federal Office of Topography plays a role in storage.

Underground projects, associations and companies that are familiar with underground drilling, e.g. Cargo Sous Terrain, geological geothermal energy, in particular deep geothermal energy, or NAGRA.

[45] https://www.svti.ch/en/federal-pipelines-inspectorate-fpi

Within the SWEET ACHIEVE project CITru is a pilot and demonstration project with the ETHZ which will test CO_2 injection in a Swiss saline aquifer using an existing deep well in the commune of Trüllikon.

Experts and researchers for the Swiss underground, such as Swisstopo, play a major role, especially in questions relating to the storage of deposited materials.

A description of the relevant players along the entire value chain of CCS projects is provided in Section 3.1.

2.6.8 National and international policies and incentives

In Switzerland

Legal basis for CO_2 transport and storage demand

Switzerland has adopted a long-term climate strategy which is reliant on the transport and storage or utilisation of CO_2 in part domestically, but also at a significant scale abroad (given very limited capacity for CO_2 utilisation and storage inland). Policy planning relies on projections and scenarios offered by the *Energieperspektiven 2050+* which includes a dedicated volume on negative emissions and carbon capture and storage (Kemmler et al. 2021) outlining the transport requirements and costs, though not examining the legal and regulatory aspects.

In May 2022 the Federal Council also adopted a dedicated report on CCS and NETs setting out the framework and next steps for scaling these technologies (Swiss Federal Council 2022). For the pioneering phase, it proposes permanently storing around 500 kt of CO_2 per year by 2030 (domestically and/or abroad, from fossil, process, biomass or atmospheric sources). Following the Energieperspektiven 2050+, it envisages scaling domestic CO_2 capture to roughly 7 Mt per year by 2050 (with interim guide values of about 1 Mt in 2035, 2 Mt in 2040 and 5 Mt in 2045). By 2050 this would comprise around 5 Mt from fossil or process sources (CCS) and 2 Mt from biomass (BECCS). Because of assumed limited domestic NET capacity, an additional roughly 5 Mt of negative emissions per year would need to be realised abroad to offset residual emissions (e.g. from agriculture) and reach net zero (Swiss Federal Council 2022).

Because domestic capacity will remain limited for many years, Switzerland's strategy relies heavily on storing CO_2 abroad. Two enabling steps have been taken: the Federal Council decided to ratify the 2009 amendment to Article 6 of the London Protocol, which permits cross-border export of CO_2 for sub-seabed storage (Swiss Federal Council 2023a); and Switzerland has begun concluding the bilateral agreements required under Article 6 of the London Protocol (and Article 6 of the Paris Agreement). The most substantive is a bilateral agreement with Norway on cross-border cooperation on carbon capture, utilisation and storage and carbon dioxide removal, signed on 18 June 2025; it is complemented by memoranda of understanding with Denmark (September 2025, including one specifically on the cross-border transport of CO_2 for permanent geological storage), Sweden (an understanding on pilot transfers of industrial CO_2 removals, 2026), the Netherlands (2022) and a declaration of intent with Iceland (2021) (FOEN 2025b). Under the Norway agreement, a coalition of Swiss firms (including Swiss Post, SWISS, Swiss Re, UBS, Zürcher Kantonalbank, the City of Zurich, IWB, and partners such as Climeworks and Neustark) announced in June 2025 the first pilot cross-border transfers of negative emissions under Article 6 of the Paris Agreement.

The Swiss domestic legal architecture for CO_2 transport and storage is also beginning to take shape. The revised CO_2 Act (in force since 1 January 2025) and the Climate and Innovation Act provide the basis for the pioneering phase to 2030, but a dedicated framework for the large-scale build-out of CO_2 transport and storage infrastructure is still to come. More concretely, the Climate and Innovation Act provides subsidies amounting to CHF 1.2 billion for technologies for climate-friendly production and processes, which may also be used for CO_2 infrastructure.

Nonetheless, barriers remain. CO_2 for transport within Switzerland is classified as waste and as a dangerous good. It is therefore subject to Swiss waste regulation and regulated under the Ordinance on the Carriage of Dangerous Goods by Road, the Ordinance on the Carriage of Dangerous Goods by Rail or Cableway, and the European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (FOEN 2025a). Classification as waste means that any CO_2 to be exported for storage requires an export licence from the FOEN. In addition, underground CO_2 storage within

Switzerland is not permitted under waste legislation, because waste disposal sites for CO_2 storage are not envisaged in the law (FOEN 2025a).

Legal basis for nationally coordinated permitting

Transporting CO_2 compared to gas or oil is different as the value will depend on policies and not on the demand of consumers. Given the need for coordinated transport paths within Switzerland and connecting with storage sites abroad (often crossing through third countries entirely), it appears self-evident that the federal government needs to be given a much stronger legal mandate to be critically involved in the planning, approval and potentially even enforcement (where there are local conflicts with land-owners, i.e. up to expropriation) of the public interest in efficient and non-intrusive transport infrastructures. Pilot activities could, however, potentially already be pursued in coordination among small groups of cantons. It may be necessary to adopt a constitutional amendment providing the federal government with the mandate to authorize CO_2 pipelines and underground storage.

While the current regulatory basis for pipeline construction puts the onus on cantons to individually allocate permits, the legal basis for federal planning of underground transport is much stronger. The Cargo Sous Terrain idea has capitalised on Art. 81 of the Federal Constitution[46] to put forward the vision of underground rail transport combined with pipeline gas transport capability. The project is, however, behind schedule: instead of 2031, the first trains are not expected to run through the tunnel system until 2036 at the earliest (SRF 2025).

To permit pipeline construction, the law for special public constructions could potentially be leveraged – thus allowing to place the overall permitting authority in the hands of the federal government. However, this law does not include any authority to command the use of private property for eminent domain, which could prove to be a significant barrier in practice. The right to claim eminent domain toward the construction of a pipeline on private land could in principle be sought through regulatory change, however, such claims would in practice face challenges as it would need to be clear that the construction is in the public interest and not solely in the interest of a company constructing and/or operating a pipeline: Causal relationship between the public interest and the chosen pipeline pathway would need to be established. On the other hand, it is likely that CO_2 transport pipelines would have to follow – as much as possible – the trajectories of existing gas pipelines, which could much facilitate planning and permitting processes and limit challenges with landownership. The legal permits need to be discussed and planned together with the ERI / SFOE, right now the rules and specifications are unclear.

These gaps are precisely what the forthcoming national CCS framework act (in response to parliamentary Motion 24.4256) is intended to address, by giving the federal government a clearer mandate over the planning, approval and financing of CO_2 transport infrastructure. The act, aimed at governing the capture, transport and storage of CO_2, is due to be submitted to Parliament by end of 2026 and, like the revised CO_2 Act, is expected to enter into force on 1 January 2031 (FOEN 2025a). The specific rules and competencies – including for pipelines and storage sites – are being developed and are scheduled to enter public consultation in 2026, so the permitting regime described here should be read as the pre-framework baseline that this legislation aims to replace (FOEN 2025a; Marxer et al. 2026).

Legal form of transport providers and financing options

In Switzerland, there are several potential legal forms of entities that could provide CO_2 transport services for carbon capture transport and storage activities. One option is like the **traditional procurement** a pure **public finance**, where the federal government and/or cantons/cities provide public funding and become the sole owners of the infrastructure. They finance the planning and construction of the infrastructure through public debt. To give the public service provider some autonomy, specific public bodies can be set up. These bodies can take different forms, such as autonomous public entities (e.g., Geneva Airport), state stock corporations under public law (e.g., Swiss Federal Railways and Swiss Post), or even private law entities (e.g., Skyguide air traffic control) (See Table 12).

Another potential option is private funding, where the CO_2 transport infrastructure is **purely privately funded** and owned. In this case, the private entity has the authority to set the pricing for the use of the infrastructure. The state can reduce the risk associated with private funding through guarantees, as outlined in Article 7 of the Climate and Innovation Act. There are two distinct forms of private funding: project financing and corporate finance. In project financing, a separate entity called a special purpose vehicle (SPV) is created solely for the construction of the project and is not recognised on the company's

[46] "The Confederation may in the interests of the country as a whole or a large part of it carry out and operate public construction works, or provide support for such construction works".

balance sheet. On the other hand, in corporate finance, the project is developed as part of an existing company, and any gains or losses are included on the company's balance sheet.

Table 12: Possible variations of organising and financing the CO_2 pipeline (adapted from Athias et al. 2019).

	Designing	Building	Financing	Operating	Ownership	Examples	Pros	Cons
Traditional procurement	Public	Private	Public	Public	Public	• Autonomous public entities (Geneva Airport) • State-owned limited under public law (SBB) • Private law (Skyguide)	• Lower costs for financing compared to private sector	• Referendum risk • Financing through budget
Private financing	Public (or mix)	Private	Private	Public (or mix)	Public	• Distinct and permanent leasehold right (Tissot Arena)	• Avoid referendum • No public budget • Spread costs through a larger area (economies of scale)	
Service contracts	Public	Private	Public	Private (≠ building)	Public	• Lease contracts paid by users (e.g. child-care centres) • Management contract (fixed price from public authority)		
PPP (same private partner for building and operating stages)	Private (or mix)	Private	Private (or mix)	Private	Public	• Availability scheme: fixed price, demand risk born by public (Administrative Centre Neumatt) • Concession scheme: demand risk with provider (Cadiom district heating network)	• Better quality as the one which is building is also operating it	• Skills are missing • Can become complex • Adverse selection like winner's curse in the bidding process • No specific legal and institutional framework for PPPs on federal level
Regulated market	Private	Private	Private	Private	Private	• Based on federal, cantonal or municipal legislation (e.g., nursing homes)		

Additionally, regulated private financing is another possibility, combining private ownership and investment in infrastructure assets with underlying regulations and incentives provided by institutional actors. In this scenario, a private entity serves as the infrastructure manager, collecting transit charges and/or subsidies to finance operations and cover investment costs. One approach to regulated private financing is the **Regulated Asset Based (RAB)** model, where the infrastructure manager operates under regulation to ensure market access, fair pricing mechanisms, and unbundling. In exchange for complying with these regulations, the public economic regulator assumes commercial risks and guarantees a reasonable and stable return on the plant investment. For example, the power grids managed by Swisscom are regulated under the supervision of Elcom.

Lastly, **Public-Private Partnerships (PPP)** offer an alternative legal form for CO_2 transport service providers. PPPs are long-term agreements between a public authority and a private partner, selected through a competitive tender process, to design, build, finance, and operate infrastructure required to provide public services. In this arrangement, the same private partner is involved in all aspects, including planning, construction, financing, and operation or maintenance. Examples of PPP projects in Switzerland include Nagra, which manages a nuclear waste repository, the Neumatt centre in Bern (including a prison), and the district heating system in Geneva (Cadiom). These partnerships combine public and private resources, expertise, and responsibilities to achieve infrastructure development and service provision objectives.

A major aspect concerning financing is the business model. An issue concerning the financing of a CO_2 pipeline will be that the network must be constructed already from the beginning taking into consideration the transport needs for peak demand in the future. Hence the specific costs for the first few transport clients would be too high and would be not interesting for them. In Germany there are discussions in the direction that the "CO_2 transport company" (CO_2 TSO) constructs the whole pipeline and gets a usage fee from the transport clients which is affordable. Over the years more and more clients will use the transport. After a certain time (e.g., 10 years) it will be recalculated whether the prices could be set in such a way that the CO_2 TSO can recover all the costs. If this is not possible, the deficit would be covered by the government. It makes sense to follow this discussion to see if it could be a solution as well for Switzerland.

A study commissioned by FOEN assessed the regulatory options for CO_2 pipelines and underground storage (T & S) in Switzerland together with the state interventions needed to realise them. See summary in Figure 48 (Worm et al. 2024). Note that various individual measures in the areas of "CAPEX-

focused support" and "Ongoing support" are each compatible with at least one of the regulatory options considered.

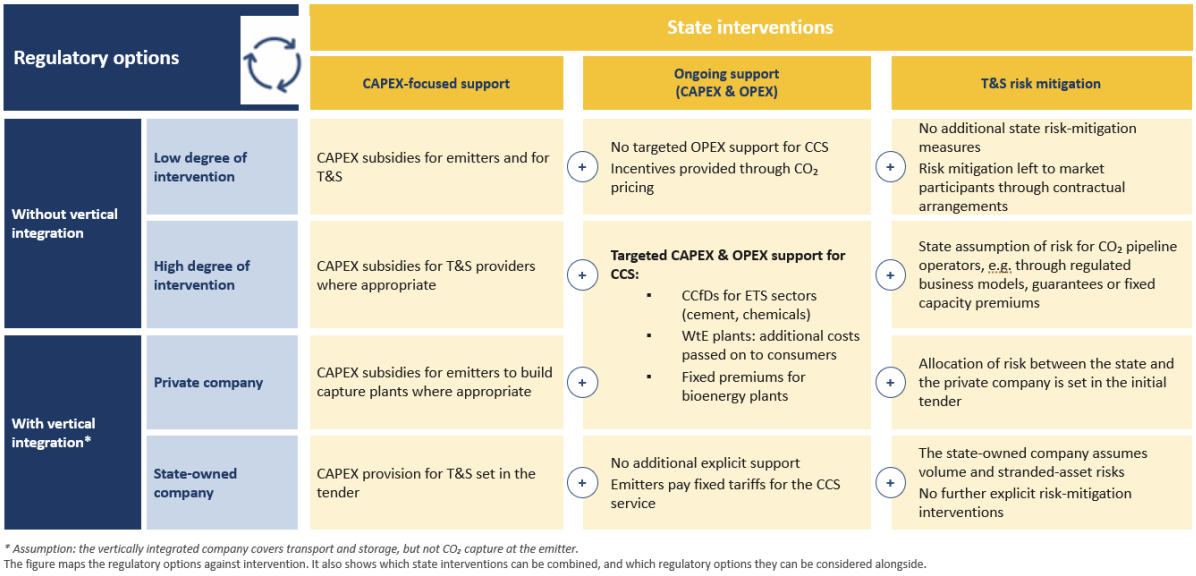


Figure 48: Recommended intervention packages in combination with the chosen regulatory framework (Worm et al. 2024)

Recommendations for action on spatial planning related to CCTS[47]

Switzerland faces the challenge of using its limited space efficiently and sustainably. Whilst above-ground spatial planning has been established for decades, the strategic use of underground space has so far been largely overlooked. However, the underground space is already characterised by tunnels, utility lines, energy infrastructure, etc. Integrated underground planning is crucial for CO_2 transport and storage, as well as for seasonal heat storage, in order to use these resources efficiently and shape the future of our rural and urban areas in a sustainable way. A lack of coordination leads to conflicts, higher costs and risks to the environment and safety.

In the view of Fachkreis Raumplanung im Untergrund (FRU), there is currently a lack of a knowledge base that brings together the expertise of various disciplines – such as law, spatial planning, construction, engineering and environmental science – and makes it accessible to the general public. The FRU has therefore decided to produce a publication that brings together knowledge from the various disciplines relevant to the subsurface.

The first version of the handbook is intended to serve as a guide or set of guidelines for public authorities and planners. Accordingly, the contributions are to be divided into three parts:

1. Theoretical foundations and knowledge transfer on various topics relating to the spatial planning for the underground.
2. Demonstrate the direct practical relevance and applicability of the underlying principles, using examples such as CO_2 transport and CO_2 storage in Switzerland.
3. Explain procedural issues in special planning and process design in underground planning and construction.

The handbook, scheduled for publication in summer 2027, is to be compiled by leading experts in the fields of law, geology, spatial planning, the environment and engineering, and will cover a range of relevant subsurface topics.

[47] This text is based on the project description for the «Handbuch zur Planung der Nutzung des Untergrunds, Version 1», April 2026.

The recommendations for spatial planning, including those from the FRU Handbook, help to increase acceptance of the transformation and enable the early involvement of all levels (federal, cantonal and municipal) in spatial planning.

Internationally

The wider regulatory picture for CO_2 transport and storage has advanced markedly. At EU level, the 2009 Directive on the geological storage of carbon dioxide (or CCS Directive) establishes uniform minimal requirements for CO_2 capture, transport and storage in the member states, including for site selection, operation and monitoring, with the aim to prevent, minimize and if necessary, remedy any CO_2 leakage. More recently, the Commission adopted its Industrial Carbon Management Strategy on 6 February 2024, setting out how the EU intends to scale up CO_2 capture, transport, utilisation and storage. It is underpinned by the Net-Zero Industry Act (NZIA, Regulation (EU) 2024/1735), which sets a binding EU-wide objective of at least 50 million tonnes per year of CO_2 injection (storage) capacity by 2030 and, for the first time, obliges oil and gas producers to contribute to developing storage capacity in proportion to their past production, creating an EU-wide push to develop operational storage. Building out the transport infrastructure to serve this target is substantial: a Commission study estimates a CO_2 transport network (pipelines and shipping routes) of up to around 7,300 km and total costs of up to roughly EUR 12 billion by 2030 (European Commission 2025; European Commission 2026b). The Commission reported in 2026 that the EU is making progress toward the 2030 injection capacity target (European Commission 2026b).

National frameworks are also emerging. In Germany, the amended Carbon Dioxide Storage and Transport Act (Kohlendioxid-Speicherungs- und -Transportgesetz, KSpTG) entered into force on 28 November 2025. It lifts Germany's previous de facto ban on CCS under the older Carbon Dioxide Storage Act (Kohlendioxid-Speicherungsgesetz, KSpG), which permitted only research, testing and demonstration with limits on total and per-project storage volumes. The new framework allows CO_2 storage, including offshore storage under the seabed, at industrial scale, and explicitly recognises the construction and operation of CO_2 pipelines for CCS/CCU (and DAC) as serving the public interest where they contribute to reducing German emissions (Hoffmann et al. 2025).

According to the IEA Climate Policies database (IEA 2026a), several other countries have adopted legislation to regulate the storage of CO_2, including Australia (sub nationally in Queensland and Victoria), Canada (sub nationally in Alberta and Saskatchewan), Indonesia (focused on EOR and use of depleted oil and gas fields), Norway, the UK, and the US (where numerous states have adopted CCS-related legislation). Such legislation typically includes provisions regarding ownership of the underground pore space, exploration and use rights, safety, permitting, and post-closure monitoring and liability, often establishing a fund to support long-term monitoring and potential remediation costs in case of leakage.

Sector-coupling and anti-trust challenges

When involving cooperation between multiple sectors, CO_2 transport may prove particularly challenging in Europe as there is no direct international state of the art for sector coupling, which is an international issue that remains largely unresolved. In the European Union, existing sector-specific regulations have been deemed inadequate to address sector-coupling technologies (Gea-Bermúdez et al. 2021). Clarifying the scope of individual parts and institutions across complex value-chains across multiple sectors can become tricky with a growing scope and increased cooperation (as would be the case with storage and utilisation hubs and clusters especially when these are permanently connected through pipelines). It is possible that further analysis will show a need for changes to the legal provisions regarding sector-coupling and anti-trust laws to allow for the credible and effective implementation of such cases. Unbundling rules, which tend to apply to electricity or gas grid operators (Tanase and Herrera Anchustegui 2023), could also apply to CO_2 pipeline operators and could prove problematic in case of infrastructure leading to the physical coupling of sectors and actors. The goal of further analysis would thus have to be the identification of potential problems and the proposal of regulatory adaptations that foster a level playing field, and ensure that the most innovative, useful, and efficient technologies can thrive and contribute to carbon management.

Classification of CO_2

Ambiguity regarding the proper classification of CO_2 – is it waste or a product - to be transported for storage abroad has proven to be a serious legal challenge under the DemoUpCarma project.[48] The initial problem was that the first isotainer of CO_2 arriving in an Icelandic port was rejected for not properly being declared and due to regulations against the disposal of foreign wastes in the country. The import

[48] See the project website: http://www.demoupcarma.ethz.ch/

could then be achieved after a certificate of origin was provided. Later a different barrier showed on the Swiss side pertaining similarly to the proper classification of the CO_2 – as a chemical good or a waste. International shipment of CO_2 for storage abroad can thus be put into question unless a consistent approach can be found that permits such activities in general or under particular conditions; varying national legislation may pose a particular challenge that may differ for each country pair between which such transports are to take place. Proper classification is necessary to ensure compliance with environmental, safety, and transportation regulations, as well as to address liability issues associated with the handling and storage of CO_2. Any leakage during transportation in international waters would need to be treated like emissions under the International Maritime Organisation (IMO).

Nonetheless, some progress has been achieved. Because CO_2 can be stored beneath the seabed, the Convention for the Protection of the Marine Environment of the Northeast Atlantic Ocean (OSPAR) and the London Protocol for the Prevention of Pollution from the Dumping of Wastes and Other Matter are relevant. While they prohibit CO_2 storage in the water column, they allow it in the seabed subject to marine environment safeguards. The 2009 amendment to Article 6 of the London Protocol permits the export of CO_2 streams for sub-seabed geological storage where the countries concerned conclude an agreement or arrangement; although it has not yet formally entered into force, a 2019 resolution allows its provisional application by parties that have accepted the amendment and submitted a declaration to the International Maritime Organization (Carbon Gap 2025). The Swiss Federal Council decided to ratify the 2009 amendment (Swiss Federal Council 2023), placing Switzerland among the countries – alongside Norway, the Netherlands, Denmark, Sweden, the UK, Belgium, Finland, Spain and France – that can rely on it. Domestically, CO_2 captured for the purpose of storage is legally classified as waste in Switzerland, so its export requires an export permit from the FOEN (Marxer et al. 2026).

Together with the bilateral climate agreements that Switzerland has started to conclude (see above), the developments under the London Protocol substantially reduce the classification and cross-border uncertainty that hampered the first DemoUpCarma shipments, shifting the remaining task toward operationalising transport logistics and scaling the arrangements.

Inconsistent transposition of EU CCS Directive

The inconsistent transposition of the EU CCS Directive among different member states and states of the European Economic Area poses significant problems (Elkerbout & Bryhn 2019). The EU CCS Directive aims to establish a legal framework for the safe and environmentally sound capture, transport, and storage of carbon dioxide. However, the transposition of this directive into national legislation varies across jurisdictions, leading to regulatory disparities and potential barriers for the implementation of carbon capture and storage (CCS) projects. Inconsistent transposition can result in differences in licensing procedures, liability rules, and regulatory requirements, creating uncertainty and hindering cross-border cooperation in CCS initiatives. This lack of harmonisation undermines the effectiveness and efficiency of CCS deployment, as it increases administrative burdens, complicates project planning and financing, and may discourage investments in this crucial climate mitigation technology. Addressing these inconsistencies and promoting harmonised transposition of the EU CCS Directive is crucial for fostering a coordinated and cohesive approach to CCS implementation across the European Union and the European Economic Area. For full compatibility and connecting Switzerland to European pipeline and storage infrastructures it will be crucial that Switzerland fully aligns its legal framework to the one of the EU CCS Directive in regards to capture and transport of CO_2 (Frattini et al. 2022).

Regulatory and industry standardisation

For interoperability, all forms of CO_2 transport will require progress toward standardisation of gas pressures, purities, and mechanical connection points as well as metering of volumes to achieve smooth interactions (Neerup et al. 2022). The same is true for safety standards, where there is already expertise and where regulations exist for example for barges – the European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways – short AND - including for inland shipping of CO_2 (United Nations Economic Commission for Europe (UNECE) 2018).

There is a need for standardisation that achieves compatibility across CO_2 transport elements in Europe (see more details in Box 3). Lack of harmonisation hinders cross-border activities and creates additional uncertainty in a sector that is already considered high-risk for investments (Neele et al. 2013). Standardisation is essential to ensure consistent product quality and safe transport conditions. Specific attention should be given to pipeline design and fracture control based on evidence.

National and local differences in regulations can significantly complicate the planning of CO_2 transportation. Local regulations, particularly in environmentally sensitive areas, may for example require specific design choices for river crossings (van den Broek et al. 2013). In such cases, trenchless

methodologies like HDD (Horizontal Directional Drilling) or microtunneling are often employed (Ziaja et al. 2018). In other cases, under similar circumstances, local regulations may be permissible for a bridge crossing. Such variations in regulations add complexity to the planning process and necessitate careful adherence to local requirements.

Regarding a level playing field, an imbalance in supportive versus restrictive policies can become problematic for Swiss entities if Switzerland adopts similar environmental protection regulations as does the EU which imply costs on the private sector, yet it does not adopt the same supportive and protective policies that the EU has. This includes a carbon border adjustment mechanism as well as various subsidies and preferential investment funds (Holzer 2021). To ensure a level playing field Switzerland may also need to mirror supportive policies more closely to the EU's.

EU Projects of Common Interest

EU Projects of Common Interest (PCI as per the EU TEN-E regulation) offer significant opportunities for the development of CO_2 transportation pipelines and other CO_2 transport infrastructures, as well as for accelerating storage site planning and development. These infrastructure projects serve to connect the energy systems of EU countries, facilitating the efficient and secure transportation of CO_2. PCIs are eligible for funding through the European Connecting Europe Facilities (CEF), providing financial support for their implementation. Additionally, PCIs benefit from accelerated permitting and authorisation processes, streamlining the development and deployment of CO_2 transport and storage infrastructure.

The relevance of EU Projects of Common Interest (PCI) for CO_2 infrastructure has grown under the revised TEN-E Regulation. CO_2 transport and storage networks are an eligible category, and the Commission's PCI/PMI lists now include a number of dedicated CO_2 infrastructure projects, which benefit from streamlined permitting and eligibility for Connecting Europe Facility funding. The current lists are published by the European Commission.[49]

For storage, the most significant development is that the Northern Lights project in Norway – the world's first open-access, third-party CO_2 transport and storage service – began operations in 2025, with the first CO_2 volumes injected and stored in August 2025. Its first phase provides up to 1.5 million tonnes per year of storage capacity; a second phase, sanctioned in March 2025 with an investment of around NOK 7.5 billion, will raise total capacity to at least 5 million tonnes per year from 2028 (Equinor 2025; George 2025). Northern Lights is one of the storage endpoints most relevant to Switzerland's plans for storing CO_2 abroad, facilitated by the bilateral CH–Norway cooperation agreement noted above.

EU Innovation Fund

The Innovation Fund is a financial instrument under the European Union's Emission Trading System, which can enable first-of-their-kind projects, including CO_2 transport infrastructure initiatives. It provides substantial funding to support the demonstration and deployment of innovative low-carbon technologies, fostering the scaling-up of technologies and the realisation of ambitious climate goals.

BOX 3: Status of technical standardisation and regulation for CO_2 quality for infrastructure

CO_2 transport has already been used for many years in different areas, such as food and beverages, in agriculture, in industrial applications, and as refrigerant and fire extinguisher. This transport of CO_2 is performed in all different phase conditions (gaseous, liquid, solid and supercritical) and using various transport modes: on road, train, inland waterways, marine shipping and pipelines. For each application a different regulation has been established with supplementary conditions depending on the transport mode and phase condition.

An overview of different purity requirements depending on the usage is given in Table 13. The transport for food grade CO_2 (food additive E290) is well established and strongly regulated. Also the use of CO_2 as refrigerant R744 allows only an impurity concentration of max. 0.005%. For both applications the transport in gas bottles or pressurised tanks is well established. For enhanced oil recovery, transport in liquid phase in pipelines has been used for decades in the United States (>8,000 km) with regulations from the American Petroleum Institute (API Recommended Practice 1192 (RP 1192), Transportation of Carbon Dioxide by Pipeline). But each pipeline might have a different specification depending on the oil/ gas field where the CO_2 is injected. Experience from gaseous pipeline transport (around 350 km) of CO_2 for greenhouse application in the Netherlands

[49] https://energy.ec.europa.eu/topics/infrastructure/projects-common-interest-and-projects-mutual-interest_en

is available as well.

The pipeline transport has been done for decades in gaseous, liquid and also dense phase. The largest experience has been gathered in the United States for CO_2 transport for enhanced oil recovery. This basis can also be used for CCS applications. For the CCS-application, further requirements might be necessary due to ship or offshore pipeline transport to the storage site for example in the North Sea. Also, the storage site as well, due to its geological conditions and the existing bore well, might add further restrictions. Several storage projects have low limits for the impurities.

As an example, the specification for the storage projects of “Northern Light” [https://norlights.com/] can be used. The last step of the transport to the storage site will be done by ship and then injected into the storage site in the North Sea. The transport in the ship will be in the liquid phase in pressure tanks. This restricts the limits for the impurities even more to avoid phase changes.

In the case of the Aramis Project, CO_2 is planned to be transported by ship and pipeline [https://www.aramis-ccs.com/]. Here again, the limits for impurities are lower for the ship transport (in liquid phase) than for pipeline (gaseous / dense). The Porthos [https://www.porthosco2.nl/en/] pipeline specification is very close to the one from Aramis.

It is only in the last few years that an initiative has been launched to develop uniform standards in the field of CCU and CCS, drawing on experience from EOR. The technical committee ISO/TC 265 Carbon dioxide capture, transportation, and geological storage (ISO/TC 265) was established in 2011; since then, it has published 17 ISO standards and is currently drafting 10 new standards or updating them to reflect the latest state of knowledge. These ISO standards form the technical basis, for example, for pipeline construction. However, they do not provide specific details on topics such as distances, risk assessment or similar matters, as these areas are usually heavily dependent on the legal context of individual countries.

Since 2024, the technical committee CEN/TC 474 Carbon dioxide Capture, Transportation, Utilisation, and Storage (CCUS) (CEN/TC 474) has also been active in the field of European standardisation, working in close collaboration with ISO/TC 265. Existing ISO standards are currently being assessed within the European context and adopted as EN ISO standards where necessary. As with EN standards, for example in the field of gas infrastructure, these EN ISO standards are adopted for Switzerland as SN EN ISO standards. In addition, further documents are now being developed that specifically considered the European regulatory context, such as the Pressure Equipment Directive and the Machinery Directive.

For the design of pipelines several standards and specifications can be found: EN ISO 27913, DNV-RP-F104 Design and operation of carbon dioxide pipelines, AMPP Guide 21352, AMPP SP21632, Wood WP3 report. In general, the design and construction itself are covered by the standards and technical directives. Specific regulations concerning permitting, risk for people and environment, safety consideration, operation and distances to other structures, buildings, etc. must be regulated for each country. For example, in the Netherlands, all these regulations have been in place for several years.

In Switzerland, no federal law is in place today to regulate the construction and operation of CO_2 pipeline infrastructure, as it is the case for the gas infrastructure. The CO_2 pipelines could already be permitted under the laws of each canton. This means that every pipeline would be treated as an individual case under the cantonal building regulation. Presently, a draft of federal regulation is in preparation, which might be ready for consultation end of 2026.

Conclusions:

- European standardisation for pipeline transport and geological storage has started and especially 2 aspects concerning CO_2 composition, are followed more in detail:
  - elaborate a standard that balances risk for the entire CO_2 infrastructure (transport and storage)
  - elaborate cost for CO_2 capture to achieve the limits of the diverse impurities.
- For the first projects the CO_2 quality specification will be directly dependent on the transport type and final storage. The more restrictive limits must be complied with for the whole chain.
- Several regulations must be made to allow cross-boundary transport in Europe with a common approach. Still some knowledge is missing or not accessible due to market
- Existing transport regulations for tanks / container by road, train can be used.

- A federal regulation for CO_2 infrastructure should be established, where also permitting, supervision, risk assessments, etc. are clarified.

Table 13: Overview of different purity requirements depending on the usage.

	CO_2 content	Other components	Reference / Comments
Food / beverage: Food additive E290	⩾ 99.9 vol% for beverages	No odour / taste $H_2O \leq 20$ppmv	[EIGA DOC 70 / 17, EIGA DOC 126 / 20], Regulation EC 1333/2008, EU 231/2012
Refrigerant R744	≥ 99.995 vol%	$H_2O \leq 5$ppmw	[Messer]
Pipeline (gaseous) transport for Enhanced oil recovery or CCS	≥ 95 mol%	$H_2O \leq 50$ ppm-mol $NO_X \leq 10$ ppm-mol $SO_X \leq 10$ ppm-mol $H_2S \leq 5$ ppm-mol $O_2 \leq 10$ ppm-mol	SN EN ISO 27913:2024 Annex A (informative)
Pipeline (dense) transport for Enhanced oil recovery or CCS	≥ 95 mol%	$H_2O \leq 100$ ppm-mol $NO_X \leq 1.5$ ppm-mol $SO_X \leq 1$ ppm-mol $H_2S \leq 55$ ppm-mol Total S ≤ 50 ppm-mol $O_2 \leq 10$ ppm-mol	SN EN ISO 27913:2024 Annex A (informative)
Pipeline transport for greenhouse application (OCAP)	≥ 99 %	$H_2O \leq 40$ ppm-vol NO and $NO_2 \leq 2.5$ ppm-vol (each) Total S ≤5 ppm-vol $H_2S \leq 1$ ppm-vol	OCAP levert zuivere CO2 aan glastuinbouwers via een pijpleiding | OCAP
Ship transport (liquid phase) to Northern Lights	≥99.81 mol-%	$H_2O \leq 30$ ppm-mol $NO_X \leq 1.5$ ppm-mol $SO_X \leq 10$ ppm-mol $H_2S \leq 1$ ppm-mol $O_2 \leq 10$ ppm-mol	https://norlights.com/wp-content/uploads/2025/06/Liquid-specification-2306251.pdf
Aramis ship transport	Bal.	$H_2O \leq 30$ ppm-mol $NO_X \leq 1.5$ ppm-mol $SO_X \leq 10$ ppm-mol $O_2 \leq 10$ ppm-mol	

Aramis pipeline transport	⩾ 95 mol%	$H_2O \leq 40$ or 70 ppm-mol $NO_X \leq 1.5$ ppm-mol $H_2S \leq 5$ ppm-mol $(H_2S + COS + SO_X + DMS) \leq 5$ ppm-mol $O_2 \leq 40$ ppm-mol	

2.6.9 Main conclusions and future research

CO_2 transport

Timing and technology. CO_2 transport is technically unproblematic: CO_2 is already moved by truck and rail in Switzerland today, and DemoUpCarma demonstrated the full logistics chain at pilot scale. What is missing is not technology but sequencing: pipelines are the only mode that scales to the volumes required, yet they must be built before the point source emitters they serve are equipped with capture, while emitters will not invest without committed transport capacity. This chicken-and-egg problem cannot be resolved by market mechanisms alone, which makes the federal government the indispensable coordinator. The forthcoming CCS framework act, due to reach Parliament by the end of 2026 and expected to enter into force in 2031, is therefore a crucial instrument – not least because permitting authority for pipelines currently rests with the individual cantons, so that federal–cantonal alignment is a precondition for any coherent routing plan.

Risks. The direct technical risks, pipeline leakage and contamination of groundwater, are manageable with established monitoring regimes and are not what constrains deployment. The material risks are structural: a delayed or absent network locks Switzerland into the high-cost pathway, and dependence on a single transit route or storage partner creates strategic vulnerability. As our research has shown, public acceptance is not a bottleneck: around 90 % of survey respondents were neutral or supportive of the transport options tested, and repurposing existing pipelines is significantly better accepted than new construction. This finding should shape routing strategy directly, and it makes the assessment of existing infrastructure for CO_2 repurposing an important option to be given priority.

Costs and financing. Transport dominates the cost of the CCS chain: at US$ 100–150 per tonne to North Sea storage it exceeds the cost of storage itself, and the difference of our assumed transportation costs between a connected and an unconnected Switzerland leads to the difference between marginal abatement costs of CHF 224/tCO_2e and CHF 1,482/tCO_2e. Several organisational and financing models are available – regulated private financing, public–private partnerships, a regulated transmission system operator, or a state-owned company – and each allocates volume risk, stranded-asset risk and cost recovery differently. No single model emerged as clearly superior; the choice depends on how much risk the state is willing to assume, and this decision cannot be deferred, because it determines whether private capital can be mobilised at all.

Actors. Two national initiatives are currently assessing the construction and operation of a Swiss network: CO_2 Pipeline Schweiz AG, founded in 2025, and a group of regional gas companies; a pre-FEED study is under way with federal and cantonal support. The oil industry is an essential partner, since decommissioned oil pipelines offer both a cost advantage and higher public acceptance than new construction, and ChemOil already covers smaller-scale transport via train. Internationally, Germany (OGE) and France are the key transit countries, with routes running towards the North Sea (DE) or to Marseille (FR), or from Monthey to Genoa or Ravenna (I). Securing PCI status under the TEN-E regulation for the relevant cross-border segments would materially improve the financing case.

CO_2 storage

Potential and dependencies. Reliability and trust are required from the storage provider, as are technical competence and flexibility in CO_2 offtake. To reduce dependencies and maintain a degree of competition, Switzerland would ideally have some domestic capacity alongside several international providers. In practice, however, domestic capacity appears limited, so Switzerland will rely on sites in the North Sea (Northern Lights, Norway) or in Italy (Ravenna), reached by pipeline through Germany,

through France to Marseille, or from Monthey to Genoa. Given this limited domestic capacity, framework agreements or state treaties of the kind concluded with Norway are essential, and they should be pursued also with Italy. CO_2 quality must also be assured (see Box 3), balancing purity requirements against the costs they impose. Long-term contracts between emitters and storage providers are a prerequisite for investment on both sides.

Risks and liability. Storage carries the risks that determine public and political acceptability: leakage from the reservoir or during injection, groundwater contamination, and induced seismicity, all of which must be assessed site-specifically and covered by long-term monitoring. The defining problem, however, is liability: the horizon extends beyond any conventional investment cycle, potentially over centuries, which makes purely private financing untenable and requires an explicit state backstop. The transfer of liability to a national fund or public body after a defined period of demonstrated integrity – analogous to NAGRA's role for radioactive waste – should be evaluated as part of the framework act, which must also settle site selection, permitting, operation and monitoring. A further legal obstacle is that CO_2 captured for storage is currently classified as waste in Switzerland and requires a FOEN export permit.

Acceptance. Geological storage is the weak point of the whole chain in public perception: 59.9 % of respondents were uncomfortable with geological CO_2 injection, against about 26 % for solid biochar stored underground. Yet 73.4 % support domestic geological storage in principle if it can be done safely. The challenge is therefore trust-building by communicating the public early on, as well as early involvement at cantonal and municipal level well before any siting decision is announced.

Actors. Norway is the principal partner, with Northern Lights the first open-access third-party storage facility and a bilateral agreement already in place; but Italy would also be an important candidate given the existing oil pipeline and storage at Ravenna. Domestically, swisstopo's 3D geological data and NAGRA's deep drilling data provide the empirical basis for any assessment, the CITru pilot in Trüllikon will generate the first real Swiss subsurface data, and the cantons hold sovereignty over the subsurface, which makes them decisive actors in any domestic storage project.

Future research

Two research gaps stand out. The first is an empirical assessment of the repurposing potential of existing Swiss pipeline infrastructure, covering technical suitability, cost and the acceptance advantage over new construction. The second is a quantification of domestic storage capacity and the associated risks, drawing on NAGRA data and the CITru results, together with the design of liability, insurance and monitoring regimes capable of spanning the relevant time horizons. Beyond these, one question remains open: how Switzerland can maintain competition and avoid strategic dependence while committing to large infrastructure investments, given that it will for the foreseeable future be a small buyer of a service supplied by a handful of foreign providers. Game-theoretic approaches and option-value analysis appear well suited to addressing it.

3 Scaling negative emissions: Stakeholders, policies, business and market structures

3.1 Stakeholders

One of the objectives of DeCIRRA Subproject 3 is to understand which actors need to be involved in the planning and implementation of the various CCUS and NET approaches, including the necessary infrastructure, in order to achieve successful financing and communication in Switzerland. This is the goal of the stakeholder analysis. In this document, the actors are already described in detail in the individual technology-specific sections. In this section, we therefore focus more on general analyses and overarching evaluations of the actors. As part of the DeCIRRA project, the actors were analysed in three master's theses, there was also a workshop that dealt explicitly with actors, and a list of NET actors was compiled throughout the duration of the project, in which both contact details of relevant persons and an allocation to various roles, technologies and activities were made. This list currently contains around 700 entries and is updated on an ongoing basis.

The relevant stakeholders along the entire CCU and CCS value chain were identified and graphically classified as part of the master's thesis by Cedric Tanner (2022) on the basis of 14 qualitative interviews (see Figure 49). In a second master's thesis, Sofia Cafaggi (2022) focussed on the actors in the biochar and timber construction sector and conducted 15 qualitative interviews with relevant people from the DeCIRRA network. Both master's theses focussed on the maturity of the various technologies, the hurdles that currently exist in Switzerland and the roles of the stakeholders in advancing the respective technologies. In these theses, the actors were analysed more on the basis of the CO_2 value chain, which can be seen in the columns in Figure 49. The rows contain the various actors involved in all of these processes. As the interviews date from 2022, some of the findings may no longer reflect the current situation.

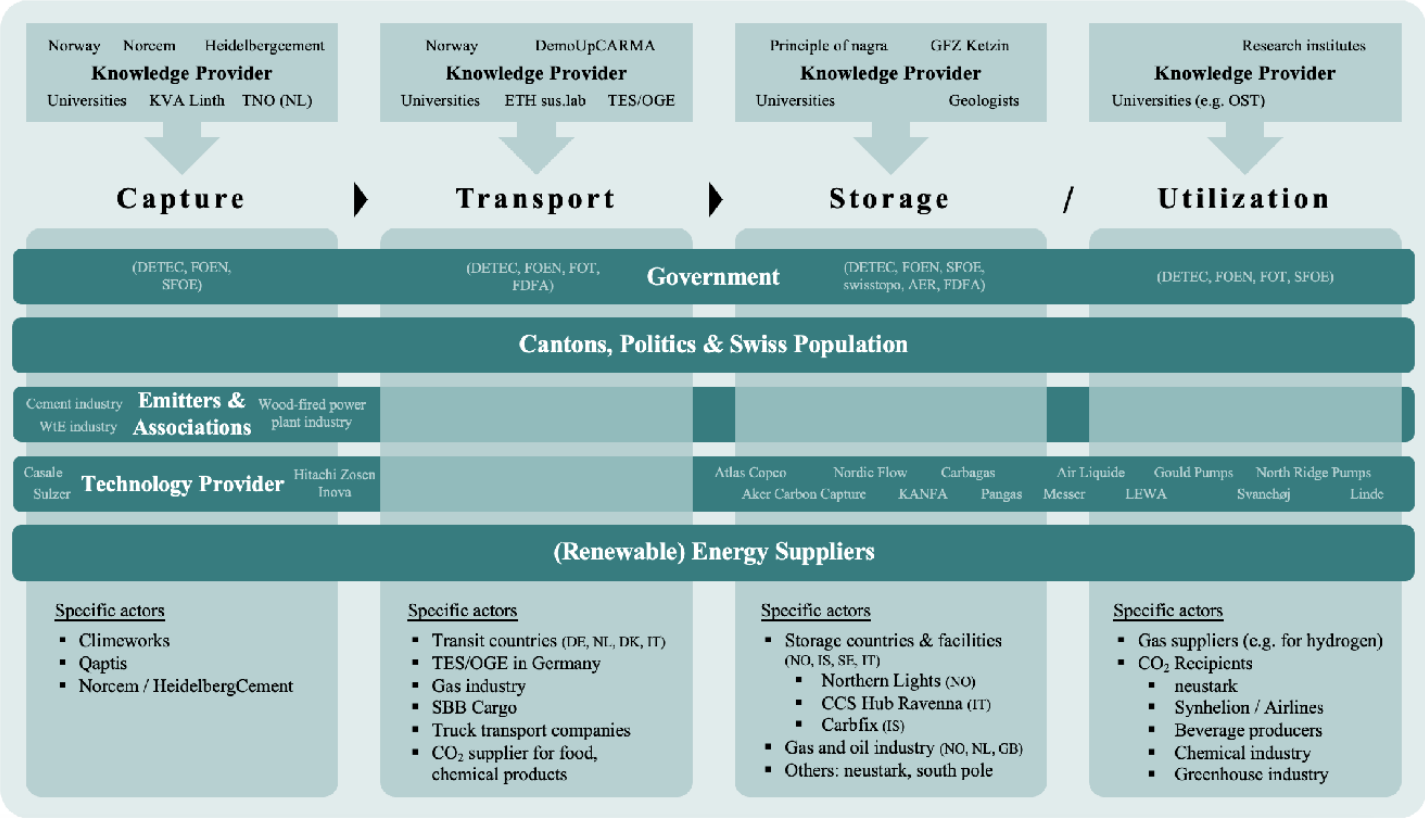


Figure 49: Relevant CCS and CCU players in Switzerland along the value chain (Tanner 2022).

Note: AER = Federal Office for Spatial Development; DETEC = Federal Department of the Environment, Transport, Energy and Communications, FOEN = Federal Office of Energy, SFOE = Swiss Federal Office of the Environment, FOT = Federal Office of Transport; FDFA = Federal Department of Foreign Affairs

As part of a further master's thesis (Dittli 2023), the NET actors were further classified and a broad quantitative survey was conducted based on the DeCIRRA list of persons, with 139 of the 385 actors contacted completing the survey. The survey asked about their roles and attitudes towards various policies, as well as the cooperation between the stakeholders.

According to our evaluation, all actors can be assigned to at least one of the following four roles: "supplier", "consumer", "regulator" and "service & support" (Figure 50). The suppliers offer NET services, e.g. carry out projects to store CO_2. The consumers emit CO_2 and need NET services, the regulators create the regulations, laws and framework conditions for the NET, and the service & support actors provide further services to support the NET, e.g. research, information, or financing. The transition from suppliers to these other supporters is fluid, as some of the suppliers are also active in research or work on regulations. In addition, almost all organisations are of course also emitters of CO_2 themselves and are therefore potential consumers. In this study, the consumers were limited to very large emitters, e.g. cement producers, etc.

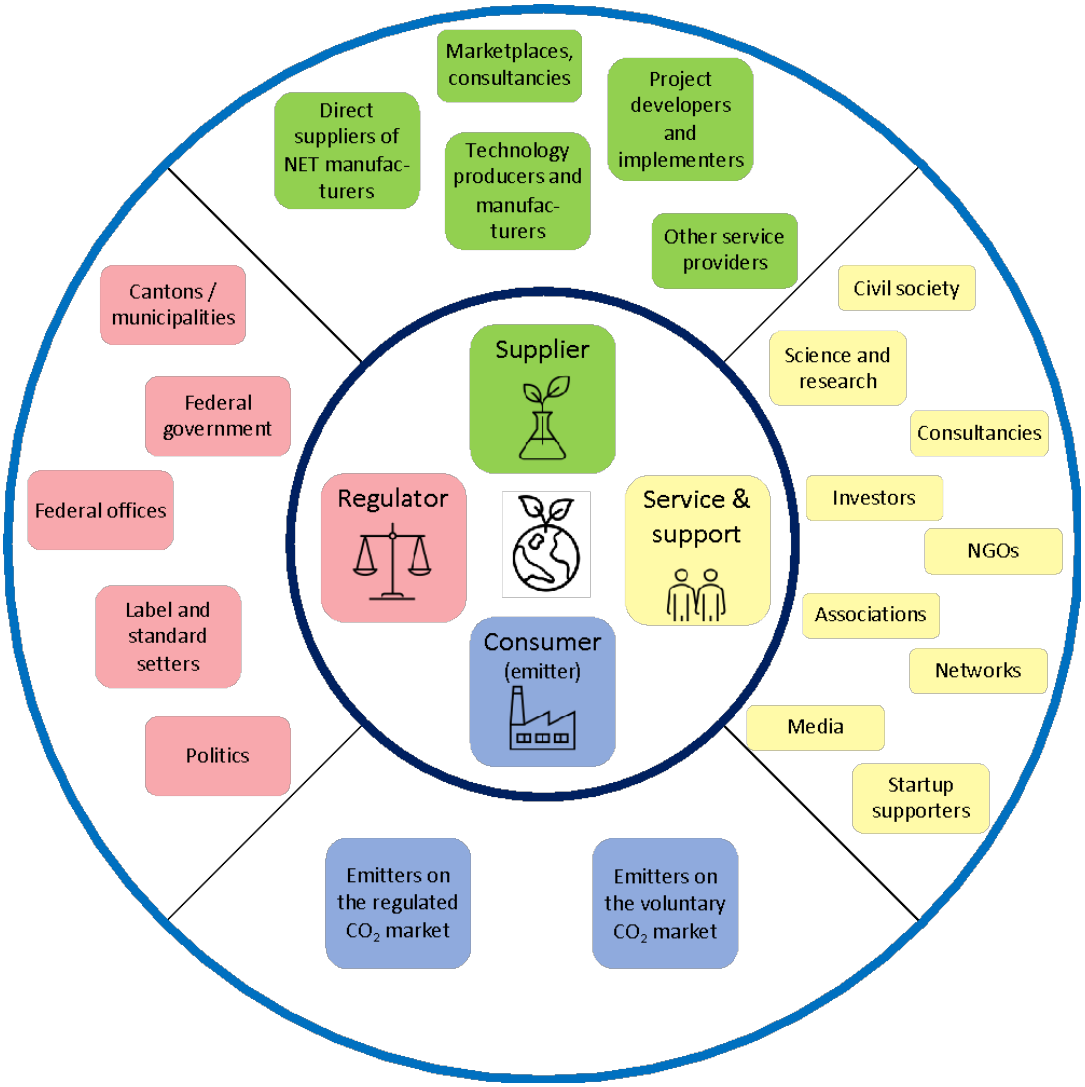


Figure 50: Roles in the NET actor network. (Dittli 2023)

Note: The four roles of supplier, consumer, regulator and service & support are shown in the inner circle, while the corresponding actor groups are listed in the outer circle. Certain actors have more than one role.

As can be seen in Figure 51, the survey reached all the different NET players. Compared to the basic population in the DeCIRRA list, there is only a slight bias towards of providers and emitters, as slightly more of the respondents categorise themselves in these categories than we have in our list.

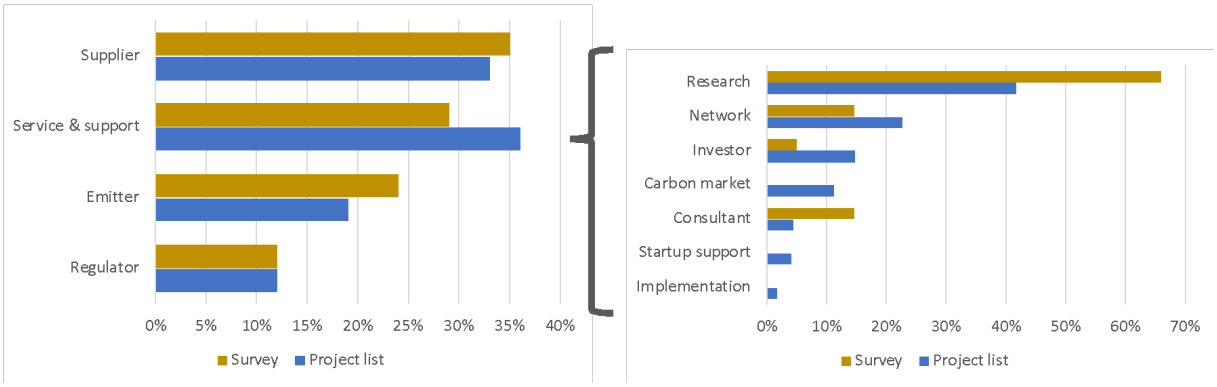


Figure 51: Roles of DeCIRRA actors in the list of 711 entries compiled for DeCIRRA, compared to the 139 survey participants (Dittli 2023).

At least one of the NETs analysed is already highly relevant today or will be highly relevant in the future for all of the actors surveyed (see Figure 52), with BECCS and CCS/CCU being mentioned the most.

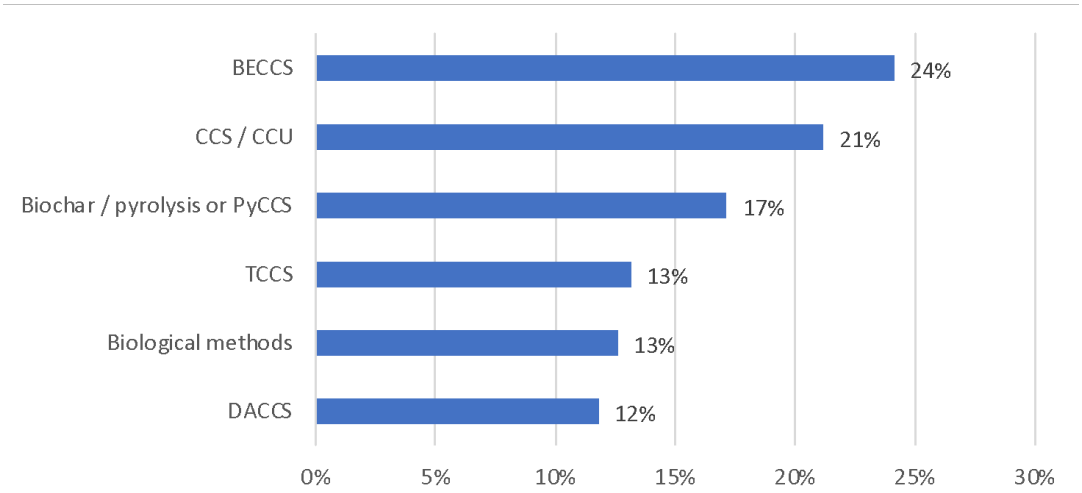


Figure 52: Show the survey answers to the following multiple choice questions: " Which of the NET technologies is currently relevant to your work or will be in the near future?" (Dittli 2023).

Most of the respondents rated their own organisation as a very important (27%) or important (46%) NET player. Respondents were also asked which other players were important. This showed that the SFOE and FOEN were rated as very important by over 80% of respondents, directly followed by the waste incineration plants (WIPs) and ETH Zurich. The councils, i.e. the National Council, the Council of States and the Federal Council, are also considered very important (see Figure 53).

The survey shows that there is already close cooperation between many stakeholders (Figure 54), e.g. with the FOEN and SFOE, which are rated as very important. The FOEN in particular stands out here and is mentioned by 71% of respondents. A possible obstacle to the rapid implementation of NET could be that there is no close cooperation with some of the emitters from industry that are classified as important for Swiss NET policy, e.g. cement (65-74%), chemicals (68%), steel (72%) and food (78%). In comparison, waste incineration plants are already quite well networked and around half of those surveyed stated that they work closely with them. Heating plants are somewhat in the middle with around 40% close partners.

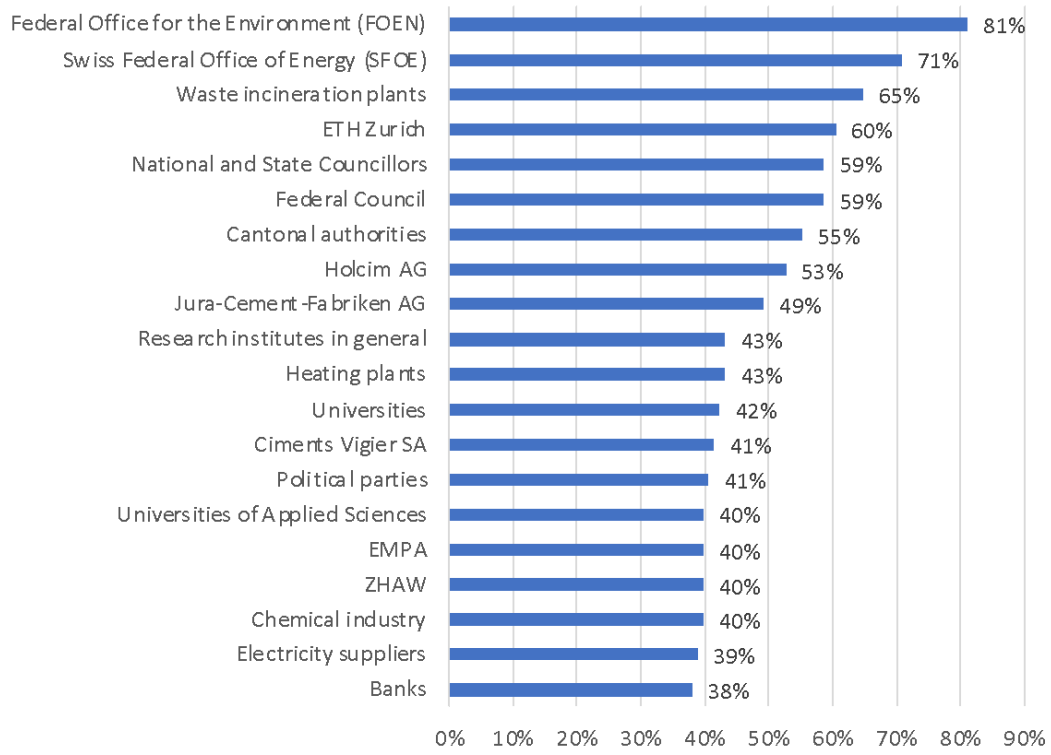


Figure 53: Actors rated as very important for Swiss CDR policy (Dittli 2023).

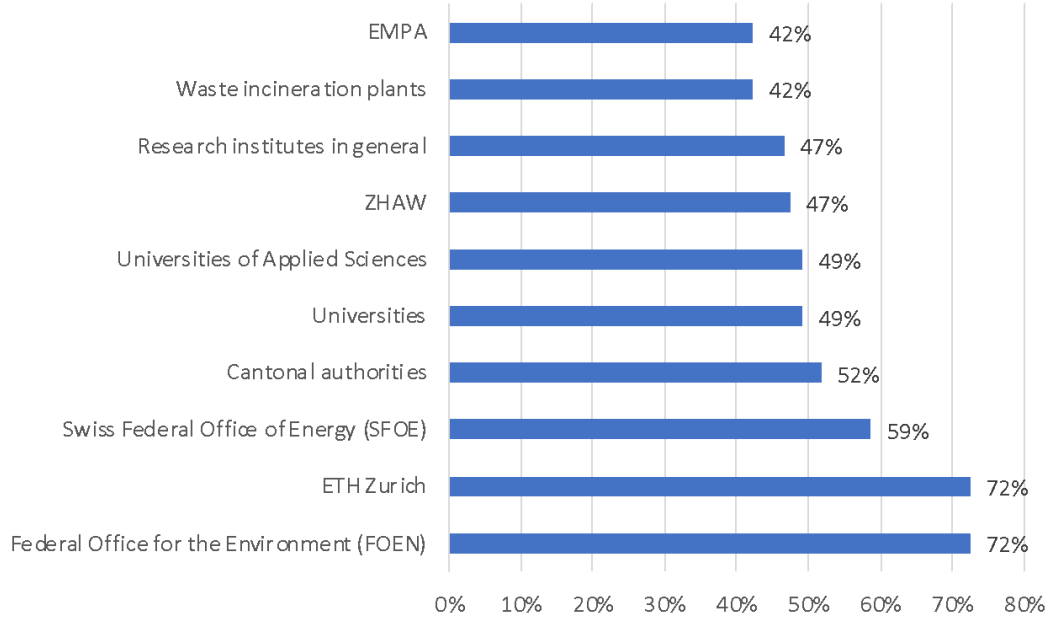


Figure 54: Actors that were mentioned particularly frequently in response to the question of whether there is close cooperation (Dittli 2023).

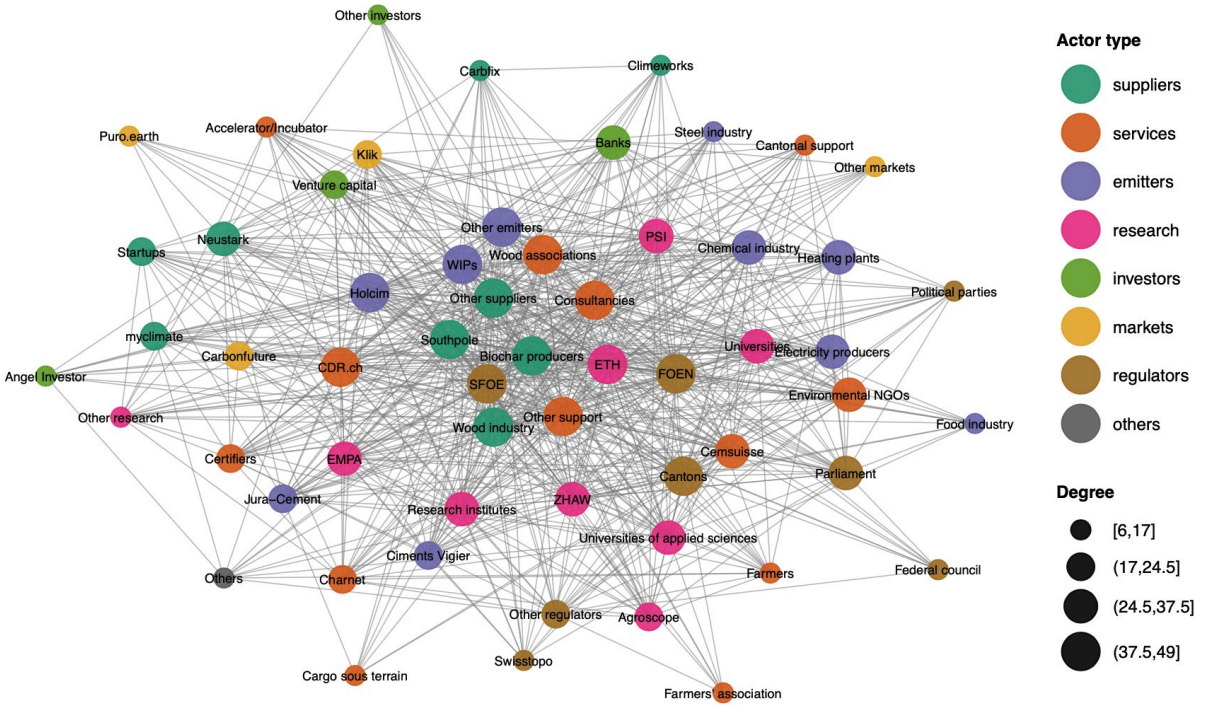


Figure 55: The close cooperation network among the interviewed Swiss NET players in 2023.

Figure 55 displays, finally, the cooperation network obtained on the basis of the survey responses from Swiss NET players. Larger circles mean players that are more central to the network, i.e., that have more ties to other players. The colours denote the different actor types, whereas the other service and support providers have been further disaggregated. Here, again, the ETH Zurich but also the central governmental agencies concerned with NET – SFOE and FOEN, as well as some current or potential suppliers of NET services, including biochar producers, the wood industry and project developers such as Southpole. It also becomes clear that the various industry associations and networking platforms – including Cemsuisse, the Swiss CDR Platform and the various wood-related associations already play an important role in connecting stakeholders.

In summary, many of the Swiss NET actors are already very well connected, and cooperation was observed to increase over the course of the project – partly on its own, but also actively supported by DeCIRRA through its expert groups.

3.2 Swiss CDR projects

In spring 2023 Swiss CDR projects were screened and compiled in a list.[50] We focused on projects that are either (planned) in Switzerland, financed from Switzerland or have a strong connection to Switzerland. We have included a few other projects in the list because they were mentioned by project partners who were involved in some way.

Of the 140 projects compiled, 44 were not directly related to CDR and were not analysed further. The 96 CDR-related projects were categorised subjectively according to their relevance to the DeCIRRA project, with around 30 projects having a high relevance and 29 a medium relevance. 71 projects are in Switzerland or have a strong connection to Switzerland. Around 42 projects have already been completed, most of them in recent years. 53 projects were still ongoing, of which around 16 can be categorised as permanent projects, which should perhaps rather be classified with the actors. These are permanent networking or funding projects. Most of the projects are funded by the SNSF or Innosuisse, and many can be found in the federal government's Aramis database.

50 https://docs.google.com/spreadsheets/d/1GpVuKlKZNSLFpDhqIazacJHAyr24nraBiZ8xjHp_cFs/edit?usp=sharing

The projects were categorised according to their focus, e.g. whether they have a technological or ethical / economic orientation. Most of the projects (82) have a technical focus and around 20 examine political or economic issues. Fewer projects deal with ethical issues. There are also projects with a more general or very broad focus that deal with various or even all focal topics.

Figure 56 below shows which technologies the projects deal with. Over 30 projects are researching issues relating to carbon capture at large point sources; many technical projects that test new materials or processes are located here. Biochar is also the subject of intensive research, with over 25 projects. Only one project can be clearly assigned to the transport of CO_2 and there are still comparatively few projects in the field of timber construction, although this technology is identified as important for Switzerland.

The analysis shows that an exchange with other projects is worthwhile to avoid duplication. As part of the DeCIRRA project, this has so far taken place via workshops. The analysis also helped us to identify other relevant experts.

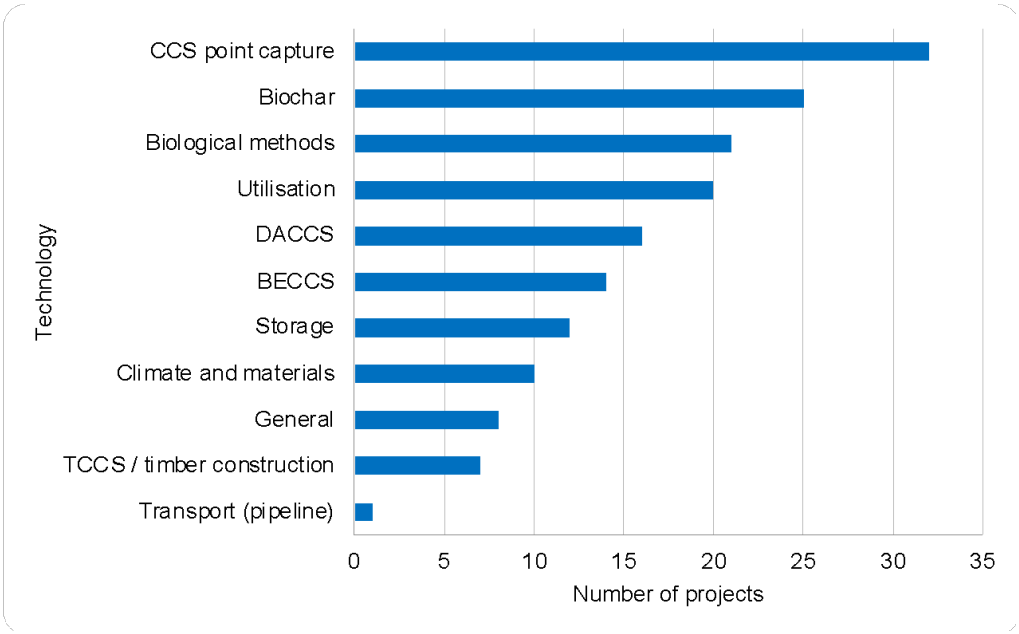


Figure 56: Number of screened projects dealing with the different technologies. Projects in Climate, Material and General could not be allocated to a certain CDR topic (status 2023).

3.3 Stakeholder policy preferences

In the previous sections, for each of the four CMA approaches, we have included a screening of policies and regulations existing in Switzerland and across the world to support the deployment of the analysed CCUS options. On this basis, first policy gaps were identified.

Policy preferences of Swiss CCUS stakeholders

The attitude of CCUS stakeholders towards different policies to support each CCUS approach was gathered and analysed in the framework of the Master thesis by Luca Dittli (2023). Respondents to the survey conducted as part of this thesis were asked to rank the following policy measures in terms of their appropriateness to support the scaling-up of the specific CCUS approach(es) that were most relevant for them (specific question: “To achieve our climate goals, we need to utilise CDR on a large scale. Please rank the following policy instruments according to their suitability to scale <selected CCUS Approach>. Rank 1 = greatest applicability, please click on all elements and move them to the right place”):

- **CO_2 price**, either through a CO_2 tax (as in the Swiss CO_2 levy) or an emissions trading system (as in the Swiss ETS)

- Issuance of **tradable certificates** for biological or technical CO_2 removal, which can be used in a CO_2 market
- **Exemption from paying the CO_2 levy** for installations that use NETs to remove their emissions or that buy carbon removal units
- **Tax credits** for carbon removal and/or carbon storage
- **Contracts** between the government and Swiss NET project developers for the provision of negative emissions at a **guaranteed price** (e.g., fixed price payments for negative emissions, or contracts for difference)
- **Mandatory targets** for emission reductions and carbon removals (e.g., take-back obligations).

These policy instrument examples were selected to cover the palette of potential policy types that can be used to incentivise CCUS technology take-up, from regulatory approaches, to economic incentives including the establishment of markets as well as other subsidy- or tax-based incentives, to direct funding for RD&D projects. Figure 57 presents an overview of these approaches, as well as several existing examples for each of them.

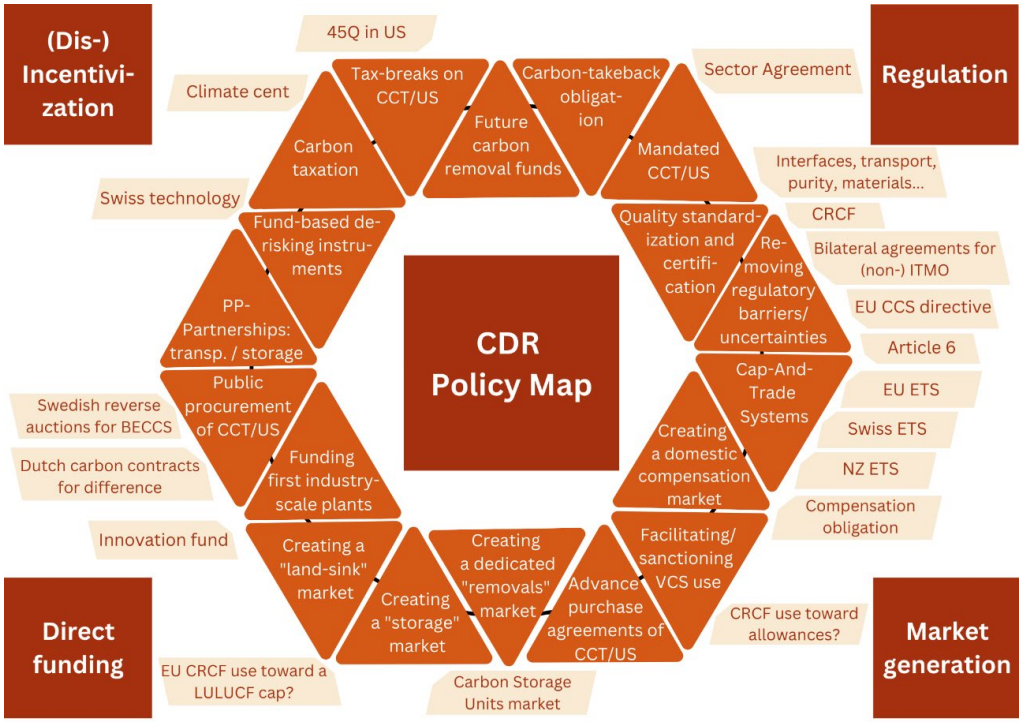


Figure 57: Overview of potential policy instruments to support CCUS approaches (Pape et al. 2023).

Survey results

To analyse the results from the survey's ranked response data on stakeholders' policy preferences, two types of descriptive statistics recommended by the literature (Finch 2022) are the calculation of each item's mean rank, whereas the lower the mean rank, the most positively the respective item was assessed on average by the respondents, as well as the calculation of marginal ranks, meaning how frequently each item was given a specific ranking. Here, it is useful to consider the top and lowest rankings, for example.

For **TCCS**, the preferred policy (with the lowest mean ranking) across all 40 respondents that assessed this technology was a **CO_2 price**, and the least preferred ones were the exemption from the CO_2 levy and tax credits. Similarly, as shown in Figure 58, the policy that was most frequently ranked best across all respondents was a CO_2 price, followed by mandatory targets. However, at the same time, mandatory targets was also the policy that was most often ranked worst (even though, on average, it did not receive the lowest mean ranking). Interestingly, stakeholders from the "other" category (including research, consultancy firms, associations, investors, NGOs) tended to rank mandatory targets either quite highly (4 times rank 1) or quite poorly (5 times rank 6). Also, while the CO_2 price was ranked highest among most stakeholder categories (suppliers of CDR services, regulators, and others), emitters most often

ranked contracts for the provision of negative emissions at a guaranteed price as their preferred choice. It is likely that emitters are mostly worried about the costs of compensating for unavoidable emissions.

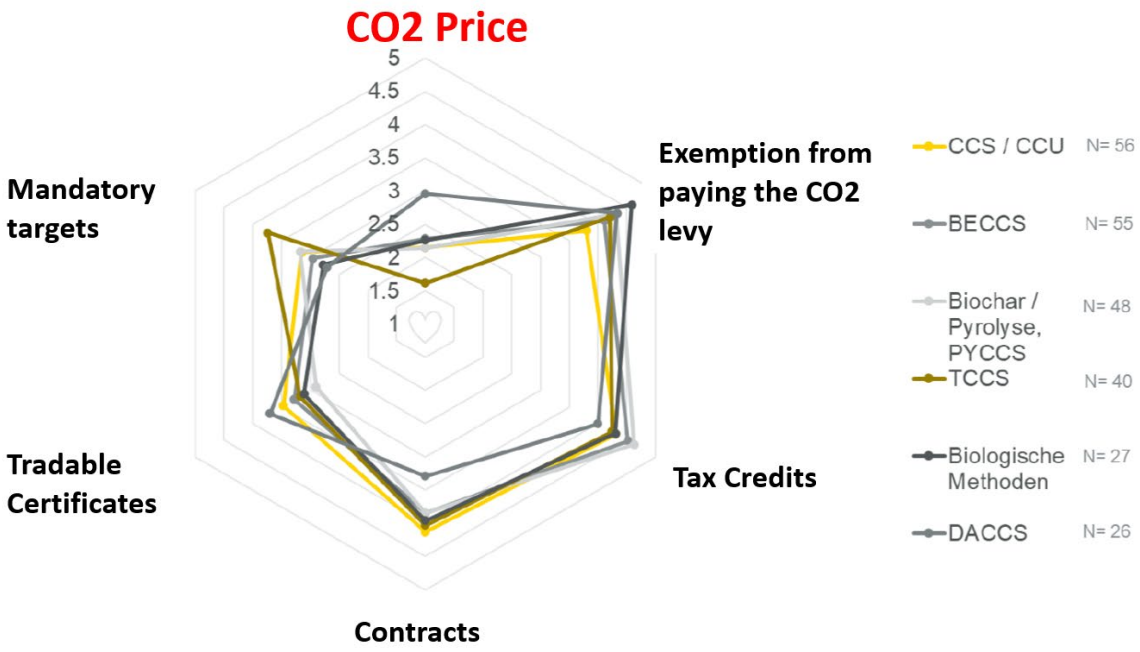


Figure 58: Ranking of policy options by technology, expert survey (lower = better ranking).

48 respondents evaluated policy options for **biochar/pyrolysis**. Among them, the preferred policy overall was also a **CO_2 price**, and the least preferred one was tax credits. In contrast, the policy that was most frequently ranked best across all respondents were **mandatory targets**, followed by the CO_2 price (Figure 58). In this case, the policy most frequently ranked worst was tax credits. Here again, there are differences across types of stakeholders. While suppliers of CDR services and emitters most often ranked a CO_2 price as their top choice, regulators and other stakeholders most often preferred mandatory targets.

For **BECCS**, the policy with the lowest mean ranking across the 55 respondents that assessed this technology was again a **CO_2 price** followed by mandatory targets, and the least preferred one was tax credits. Accordingly, the policy that was most frequently ranked best across all respondents was the CO_2 price, followed by mandatory targets. The policy most frequently ranked worst was tax credits. As in the case of biochar, we see that suppliers and emitters most often ranked a CO_2 price as their top choice, while regulators and other stakeholders most often preferred mandatory targets. In contrast, for emitters, mandatory targets were the least preferred policy option. Tax credits seem to be particularly unpopular among regulators and other stakeholders, but, surprisingly, also several suppliers of CDR services ranked tax credits lowest.

Survey respondents were also asked to rank their policy preferences for **CCS/CCU** in general. Among the 56 respondents that assessed policy options for these technologies, a **CO_2 price** was most often ranked as the top choice, and also received the lowest mean rank (i.e., it was the preferred policy overall). Mandatory targets closely follow as the second policy most frequently ranked top and with the second lowest mean rank. Tax credits are the least preferred policy choice according to both statistics. Again, we see differences across stakeholder types, with suppliers and emitters clearly preferring CO_2 prices, while regulators (from which we only had 1 respondent for this technology type) and other stakeholders most frequently preferring mandatory targets.

26 respondents evaluated policy options for **DACCS**. Among them, the policy ranked best on average was **mandatory targets**, followed by a CO_2 price. Both policies were tied in being most frequently ranked top. The least preferred policy option in terms of mean rank was exemption from the CO_2 levy. The policies most frequently ranked worst were the exemption from the CO_2 levy and tax credits. Interestingly, the two suppliers of CDR services that answered this question chose tax credits and contracts as their preferred policy, followed by the CO_2 price or mandatory targets in rank 2. Their least

preferred policy option was an exemption from the CO_2 levy. Also interesting is that not only regulators, but also emitters most frequently regard mandatory targets as the best policy to support DACCS. For the case of emitters, this is different than their preferences with regards to BECCS, biochar and CCS/CCU. Also in contrast to previous results, for DACCS, other stakeholders most often rank CO_2 prices, closely followed by contracts, as their preferred support policy.

Finally, respondents were also asked to rank policy options for biological CCUS approaches. 27 answered this question. Among them, while **CO_2 prices** received the best mean ranking, **mandatory targets** were most frequently ranked as the preferred choice. Tax credits received the worst mean ranking, and both tax credits and contracts were the policies most frequently ranked worst. Across the various types of stakeholders, while mandatory targets are most frequently ranked top by suppliers, emitters (in this case, tied with contracts) and other stakeholders, the CO_2 price was most frequently preferred by regulators.

Overall, across all technologies, there seems to be **broad consensus that a carbon price is a central policy** that is needed to move CCUS technologies forward in Switzerland, but there is **also strong acceptance that other instruments** are needed, **in particular mandatory targets**. While both suppliers and emitters seem to have a stronger preference for carbon prices, regulators and other stakeholders prefer mandatory targets somewhat more.

Other, maybe more innovative policy options, such as tradable certificates for carbon removal, contracts for the provision of negative emissions at a guaranteed price, or tax credits, seem to be either not very positively regarded or not very well understood among the surveyed stakeholders. For the case of tradable certificates, in particular, the difference to a more general CO_2 price may not have been understood by all respondents. The case of tax credits is also interesting. This is the policy option that was most often ranked worst across all CCUS approaches and also by most stakeholder types. Nonetheless, tax credits are the central policy instrument that the US and Canada have adopted to help deploy CCUS technologies at scale. These results suggest that **more information and awareness about alternative policy options** (beyond CO_2 prices and mandatory targets), their design options and strengths and weaknesses **may be needed** among CCUS stakeholders in Switzerland. Furthermore, as pointed out by some respondents to the survey, more information on specific conditions under which the selected technologies and/or policy instruments are deployed is necessary for a better informed ranking.

Responses to open-ended questions

Beyond the ranking of these specific policy instruments, respondents to the survey were asked to mention any **further policy measures** that they consider necessary to support the development and testing of CDR technologies in the short term till 2030, and to support their broad deployment until 2050. We grouped those responses that were equivalent or very similar in spirit, counted them, and classified them. The results can be found in the Appendix 3. Table A2 consolidates the responses (mostly in German) about necessary policy measures until 2030, while Table A3 does the same for the responses on policy measures until 2050.

The most frequently mentioned policy measures for the period **up to 2030** include the provision of financial support for research, development and demonstration projects; securing, supporting or simplifying the financing for CCUS projects or installations; as well as a call for clear and stable framework conditions and regulations to provide stable framework conditions for investors. In addition, many respondents asked for clear targets for CO_2 reduction and removal, as well as for simplified regulations (including, for example, simplifying the permitting process for CDR facilities).

Up to 2050, the two measures most frequently mentioned are the introduction of mandatory CDR targets and/or pathways, including sanctions for non-compliance and possibly differentiated by sectors, as well as the implementation of the CO_2 transport and storage infrastructure. Furthermore, several respondents asked for the introduction of take-back obligations under which firms are obliged to compensate their remaining emissions with CDR certificates; mandatory emission reduction targets; clear and sufficient regulatory frameworks; ensuring support from the population; a continuously increasing CO_2 price; as well as strengthening of international cooperation, particularly with the EU.

Finally, respondents to the survey were also asked to propose **measures to support the development of transport and storage capacities**. Table A4 in the Appendix consolidates these responses (again in German). Clearly, the legal and regulatory aspects are the ones most frequently mentioned by respondents, including establishing clarity or harmonising the legal requirements for the international CO_2 transport and establishing bilateral agreements with countries with storage capacity to secure

storage space for Switzerland. Nonetheless, finding storage capacities within Switzerland is also a key priority among respondents. Interestingly, there are some opposing opinions on whether in-country storage or storage abroad should be preferred. The development of the national-level CO_2 transport infrastructure, including the regulatory framework, planning and implementation are also priorities. While several respondents argue that such infrastructure should be publicly provided ("similarly to the road network"), some others point out that the private sector should be the provider, but with support (e.g., in form of investment guarantees). Another aspect mentioned several times is the importance of securing political and societal support, both nationally and locally in places where the necessary infrastructure will be built. Finally, the responses also illustrated a debate on the actual need for CO_2 transport and storage infrastructure, with a few respondents arguing that a much stronger focus should be given to emission reduction measures (including sufficiency and reduction of the consumption of high-emitting goods), and others highlighting that biological storage (e.g. in biochar or in construction timber) offers many more co-benefits than underground storage, and should therefore be preferred before investing in such massive infrastructure.

Workshop results
A similar question regarding how the six described policy options would be ranked was asked during the DeCIRRA Workshop on Pseudo-Merit Order and Policies and Measures that took place on 10 May 2023. The workshop brought together 21 experts, including representatives from research institutions, but also startups, waste incineration plants, biochar producers, NGOS, association and consultants. Experts were grouped in terms of the specific CCUS approaches being investigated in DeCIRRA, and their answers represented the group consensus. For BECCS, the policy options that were ranked highest were mandatory targets and a CO_2 price, while the policy with the worst ranking was tradable certificates. For biochar, the best ranked policy options were equally mandatory targets and CO_2 prices, with the worst ranked being contracts. For TCCS, the group ranked CO_2 prices and tradable certificates highest, with contracts receiving the worst ranking (two policy measures, tax credits and exemption from the CO_2 levy, were not ranked by the group). For DACCS, finally, the group ranked mandatory targets and tradable certificates as the best, and exemption from the CO_2 levy as the worst policy option.

3.4 Current state of voluntary CDR market

The global market for carbon dioxide removal (CDR) has grown considerably in recent years, though it remains at an early and structurally fragile stage. As of May 2026, more than 47 Mt CO_2 have been traded historically and approximately US$ 12 billion invested worldwide – yet only around 1.37 Mt, roughly 2.9% of total sales, have actually been delivered (CDR.fyi 2026) as shown in Figure 59. This gap between contracted and realised volumes reflects the forward-looking nature of most CDR purchases, where buyers commit years in advance of physical delivery. To put the scale of the entire durable CDR market in perspective: the broader voluntary carbon market issued approximately 287 Mt CO_2 credits in 2024 alone, with nature-based solutions – primarily forests – representing the largest share. The entire historical volume of durable CDR ever contracted (47 Mt) thus amounts to roughly one sixth of a single year's forest credit issuance, underscoring how nascent technological carbon removal remains relative to established nature-based markets (Climate Focus 2025).

Purchased volume grew roughly 50x between 2022 and 2025, driven largely by a small number of large buyers (notably Microsoft), while delivered volume grew far more slowly, since most contracts are multi-year offtakes fulfilled over 2025-2035. The gap between the blue and green bars illustrates how much of today's market is future promise rather than realised removal.

The market is dominated by voluntary purchases, and its structure is highly concentrated on both the supply and demand side. By delivered volume, biochar is the clear leader: BiCRS methods accounted for 91% of delivered volume in 2025, with biochar at 80% of total delivered volume, while BECCS led purchases at 69% of contracted volume (Figure 60). In Q1 2026, biochar carbon removal accounted for 93% of contracted volume and was the method used in all of the top five transactions. On the supply side, Exomad Green alone accounts for around 60% of all biochar credits sold since 2022. On the buyer side, Microsoft accounts for 36.4 million tonnes, or 78.5% of total disclosed durable CDR tonnes contracted as of April 2026, while Frontier-linked buyers account for a further 4%. However, a structurally important counterpoint is that buyers outside Microsoft and Frontier account for 90% of delivered and 94% of retired tonnes to date, meaning the delivery side of the market is significantly more diversified than the contracting side suggests. This extreme concentration in purchasing nonetheless creates structural fragility: a shift in a single buyer's procurement behaviour, as recently observed with Microsoft's pause in CDR commitments, can materially destabilise investment conditions for CDR providers across the market (Berends 2026).

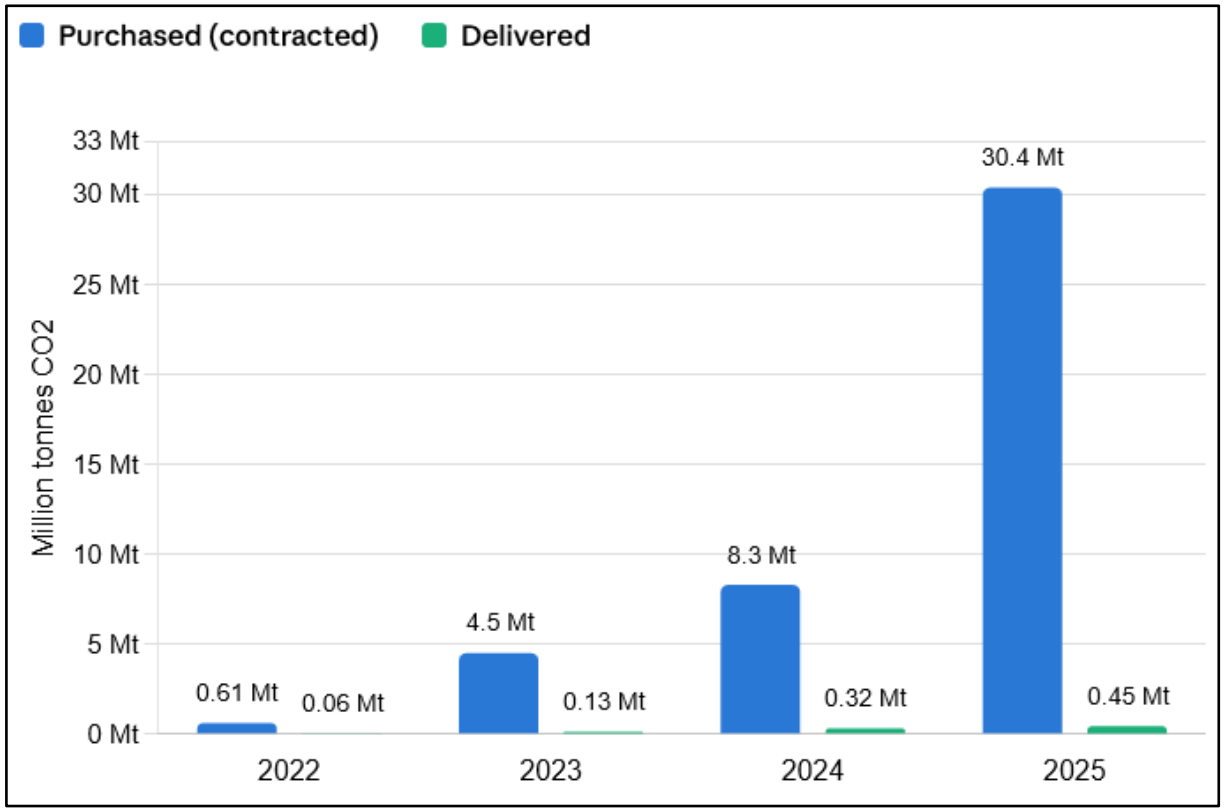


Figure 59: Worldwide volumes of durable carbon dioxide removal (CDR) that companies have contractually purchased ("offtakes") versus the volumes that suppliers have actually delivered, by year, in Mt CO_2 (Source: CDR.fyi year-in-review and market update reports (2023-2026); 2022 delivered figure is an estimate derived from reported year-over-year growth rates).

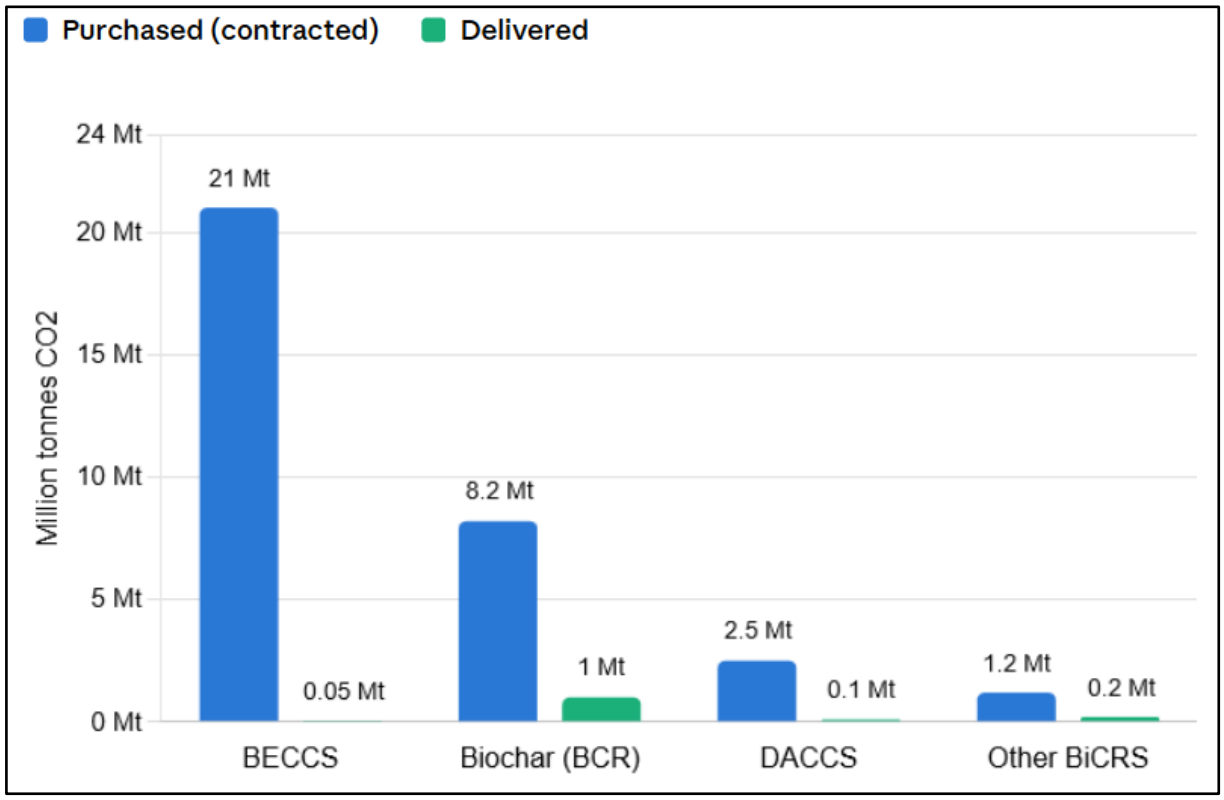


Figure 60: Worldwide volumes of durable carbon dioxide removal (CDR) that companies have contractually purchased ("offtakes") versus the volumes that suppliers have actually delivered, broken down by removal technology, in Mt CO_2 (Source: CDR.fyi market update and technology snapshot reports (2025-2026).

BECCS (bioenergy with carbon capture and storage) dominates purchased volume by far, but has delivered almost nothing to date, since most BECCS offtakes are multi-year contracts tied to plants still under construction. Biochar (BCR), by contrast, is the smallest purchased category shown here but the clear delivery leader, reflecting its shorter production cycle and greater technological maturity. DACCS and other BiCRS pathways remain small on both purchased and delivered volume. Linear y-axis, so bar height is directly proportional to tonnage.

Compliance-based demand does not yet provide a broad foundation. While the EU ETS does not include mechanisms to credit negative emissions, the European Commission's ETS revision proposal from July 2026 envisages a limited increase in the ETS cap to establish a centralised purchase of CRCF-certified domestic BioCCS and DACCS removal units to be managed by the Commission itself. The resulting legislative changes are expected to be adopted in the first quarter of 2027 (Carbon Gap 2026). The Swiss ETS, meanwhile, has allowed installations to account for carbon capture and storage (and, under certain conditions, foreign biogas use) since the revised CO_2 Act entered into force on 1 January 2025, though this remains narrower than a general CDR crediting mechanism and does not extend to methods like biochar or HWP-based storage (ICAP 2025; Net Zero Compare 2025). The absence of broader regulatory demand for most CDR pathways remains a structural barrier to investment, leaving the market still heavily dependent on voluntary corporate commitments whose continuity cannot be guaranteed. (Lagler 2025; Eichler et al. 2025).

3.5 Results of business model analysis

This section describes the results for business models, which take findings from two bachelor theses, many expert interviews and discussions and three expert workshops into account.

First, Lagler (2025) applied Gassmann et al. (2013) Magic Triangle framework to 30 European CMA companies and identified eight distinct business model types, which cluster into three overarching logics:

Technology-oriented models generate revenue primarily through the sale or licensing of CMA equipment. Customers are industrial emitters, agricultural operators, or facility managers seeking to integrate CMA into existing processes. This model is most prevalent among DACCS hardware providers and biochar pyrolysis equipment manufacturers. Revenue is decoupled from CO_2 certificate prices, providing relative insulation from market volatility, but also limiting direct financial benefit from carbon market growth.

Certificate-based models generate revenue primarily through the sale of verified CO_2 removal certificates to voluntary market buyers. This model is dominant among DACCS operators (running their own facilities) and biochar producers. Revenue is directly exposed to voluntary market prices and demand concentration risks; the model's viability is therefore contingent on sustained and growing corporate demand.

Hybrid models combine multiple revenue streams – typically CO_2 certificates, physical product sales (biochar, energy, heat), and equipment or service revenues – generating greater resilience to individual market fluctuations. The BECCS energy-certificate mix and biochar product-certificate mix fall into this category. Hybrid models demonstrate the highest commercial viability across the analysis, as the combination of revenue streams enables cost coverage even at lower individual price points.

Key activities of CMA businesses

The "How" dimension of the Magic Triangle addresses, as described above, the question of how value is delivered and activities are carried out. As part of the DeCIRRA project, the development of an overview of typical CMA key activities was initiated (Figure 61). The aim is to better understand the value creation architecture and activities of CMA providers. This overview does not yet claim to be exhaustive. It maps the core activities identified on the basis of the literature and interviews and workshops from the DeCIRRA project by Gaido and Marchand (2026 unpublished results).



Figure 61: Key activities of CMA businesses derived from stakeholder interviews (own illustration).

For the activity "Use of CO_2 / Char" the product used or replaced depends on the technology. So in BECCS the resulting CO_2 could be used for methanation or generation of SAF or also in the food industry. For hydrochar/biochar the resulting char could be used to replace fossil coal in cement or the metallurgical industry. Then certainly this is no NET but could provide a means to start scaling up the NET production industry providing an early revenue stream.

Interviews showed that across all technology types **Monitoring, Reporting, and Verification (MRV)** competence has been strategically internalised as a core activity. Rather than outsourcing certification and measurement to third parties, Swiss CMA providers are building proprietary MRV capabilities. This reflects both the reputational imperative of credibility in a market where greenwashing concerns are acute, and the practical challenge that standardised MRV methodologies for many CMA approaches do not yet exist.

Secondary core activities vary by technology: BECCS providers prioritise CO_2 transport and storage logistics partnerships; DACCS providers focus on sorbent and equipment development; biochar providers emphasise biomass supply chain management and quality certification; TCCS providers concentrate on carbon accounting methodology development.

Outsourced activities centre on legal and regulatory affairs, financial structuring, and public communication, areas where small CMA providers lack specialist internal capacity.

Unrealised business model ideas identified by Gaido (2026) include public CDR procurement schemes (providers consistently identified this as a high-impact near-term measure), Carbon Contracts for Difference (desired but unavailable), and long-term offtake agreements with municipal utilities. The structural blockades preventing realisation are regulatory (absence of a CDR recognition framework) rather than commercial or technological.

The triple market failure in CMA

The synthesis of findings across all our studies reveals a consistent structural diagnosis: CMA scaling is constrained not primarily by technological immaturity but by a triple market failure comprising (i)

absent price signals for CO_2 removal in compliance markets; (ii) missing CO_2 transport and storage infrastructure as a public good; and (iii) the non-recognition of CO_2 removal as a legally remunerable decarbonisation service (Gaido 2026). This diagnosis aligns with the broader CDR policy literature (Honegger et al. 2021; Oh et al. 2025) and extends it with empirical grounding in the Swiss and European contexts.

The Technology Readiness Level framework, while useful for characterising individual technologies, is insufficient to explain deployment gaps. Biochar is at TRL 9 yet faces regulatory non-recognition of hydrochar storage. TCCS is at TRL 9 yet faces methodological additionality challenges. The relevant analytical construct is not TRL alone but the three-dimensional readiness framework proposed in the CMA literature (UNECE Task Force on Carbon Neutrality n.d.) encompassing technological, commercial, and social readiness. The primary deficit across Swiss CMA lies in commercial and regulatory readiness, not in technical capability.

The coordination problem

A finding that also cuts across all analysis is that no single actor can develop a viable CMA business model in isolation. CCS/CCU deployment requires coordinated action across emitters, technology providers, infrastructure operators, and government (Tanner 2022). Biochar and timber NETs require aligned standards, market linkages between producers and buyers, and accepted carbon accounting methodologies (Cafaggi 2022). Swiss NET actors perceive strong mutual dependence, yet collaboration gaps persist, particularly between established policy actors and commercially active NET operators (Dittli 2023).

This coordination challenge is exacerbated by the voluntary market's current demand structure. The concentration of CDR purchases among a small number of large corporate buyers (Berends 2026) creates systemic vulnerability for providers whose business models depend on certificate revenues. The Microsoft purchasing pause in 2026 materially disrupted voluntary market stability illustrating why regulatory demand signals are not merely desirable but structurally necessary for capital-intensive CMA investment.

Business model resilience and the hybrid advantage

The analysis of European and Swiss CMA business models points to hybrid revenue models which combine certificate sales, physical product revenues, and energy outputs to demonstrate the greatest commercial resilience. This finding has direct implications for both business strategy and policy design. Policies that support only one revenue stream (e.g., subsidising only CO_2 certificate price premiums) may fail to create the conditions for financial viability in capital-intensive technologies. Policy instruments should be designed to facilitate the development of multi-stream revenue architectures, particularly for DACCS, where no secondary product revenues can compensate for the absence of strong certificate prices.

The strategic internalisation of MRV competence by Swiss CMA providers represents both a competitive differentiation opportunity and a potential coordination inefficiency. If each provider develops proprietary MRV systems independently, standardisation is retarded, which is ultimately disadvantageous for scaling of certificate markets. Public investment in shared, open MRV infrastructure or standard-setting processes could simultaneously reduce provider costs and accelerate market development. A longitudinal study of CMA business model evolution alongside regulatory development would help clarify whether hybrid revenue models remain dominant, or whether compliance market integration allows simpler certificate-focused models to achieve viability.

Switzerland's specific context

Switzerland presents a distinctive CMA landscape shaped by three factors absent or less prominent in the European context: (i) the absence of domestic geological CO_2 storage, making Switzerland more dependent than most European countries on international storage infrastructure and bilateral climate agreements; (ii) the suspension of the BFE demonstration funding programme, which has created a particularly acute valley-of-death gap for CMA at pilot-to-demonstration stage; and (iii) the advanced development of biochar as a NET, with Switzerland having some of the most sophisticated biochar value chains in Europe, yet facing binding constraints from regulatory non-recognition and agricultural application limits.

The Federal Council's two-phase CMA strategy – a pioneer phase to 2030 (targeting 500,000 tCO_2 stored) and a scaling phase to 2050 (targeting 7 Mt CO_2/year domestically) – is structurally sound but currently undersupported by the policy instruments necessary to activate either phase. Public

procurement of CDR certificates, as identified by Gaido (2026), could serve as an immediate demand-side activation mechanism requiring no new legislative authority.

Analysis of SWISS CDR landscape

To make already ongoing Swiss innovations more visible we conducted a desk research of all known CMA activities in Switzerland.

Figure 62 shows the structure and some results of this analysis. The key activities were chosen according to the analysis shown in Figure 61.

Organisation	URL	Founding Year	Technology	CDR Pathway	Phase	Size	Biomass Production / Reuse	Tech Operations (Carbon, CO_2)	Tech Operations (Storage)	Carbon Market	Financing	Ecosystem & Advisory	Energy, Co-Benefit Production
Neocarbons SA	https://v	2019	BiCRS	Microalgae CO_2 capture & valorisation	Pilot / Demo	1-10	✓	✓	✓				✓
Neustark AG	https://v	2019	CO_2 mineralisation	CO_2 mineralisation in demolished concrete	Scale-up	51-200		✓	✓	✓			
Niatsu GmbH	https://n	2024	All	Food product CO_2 footprint calculator	Early commercial	1-10				✓		✓	
Openly AG	https://v	2008 / 2024	Biochar	Biochar in buildings — C-sink manager & developer	Early commercial	1-10			✓	✓		✓	
Pflanzenkohle Schweiz AG	https://v	2022	Biochar	Biochar production — regional biomass feedstock	Early commercial	1-10	✓	✓	✓				
Projets21 SARL	https://v	2019	All	CO_2 accounting, advisory & ISO 14001 support	Established	1-10				✓		✓	
Pyronet	https://v	2021	Biochar	Pyrolysis heating systems with biochar output	Early commercial	1-10	✓	✓	✓				✓
Qaptis Sàrl	https://v	2021	CCS	Mobile onboard capture for truck emissions	Early commercial	1-10		✓	✓				
recoal AG	https://r	2023	BiCRS	Waste biomass to negative emission coal	Pilot / Demo	1-10	✓	✓	✓				
Sixteen44 SA	https://v	2024	CCS	Atmospheric methane removal, PACT technology	R&D	1-10		✓					
South Pole Suisse AG	http://ww	2011	All	Carbon market project development & offsetting	Established	501+				✓	✓	✓	
Stadt Zürich, erz	https://r	2025	BECCS	CO_2 capture from sewage biogas plant	Pilot / Demo	municipal	✓	✓					✓
Storra Dynamics GmbH	https://v	2025	CCS; DAC	Subsurface CO_2/H_2 storage monitoring software	Pilot / Demo	1-10			✓			✓	

Figure 62: Extract of the list of all identified CMA innovative activities within Switzerland. The full table is available as a google sheet.

As of July 2026 we have collected the information for 64 CMA businesses in Switzerland. Most of them are in Pilot/Demonstration to Early commercial Phase (65%). That only 6% are in Scale-Up phase proves our point that scaling up is currently very difficult (Figure 63).

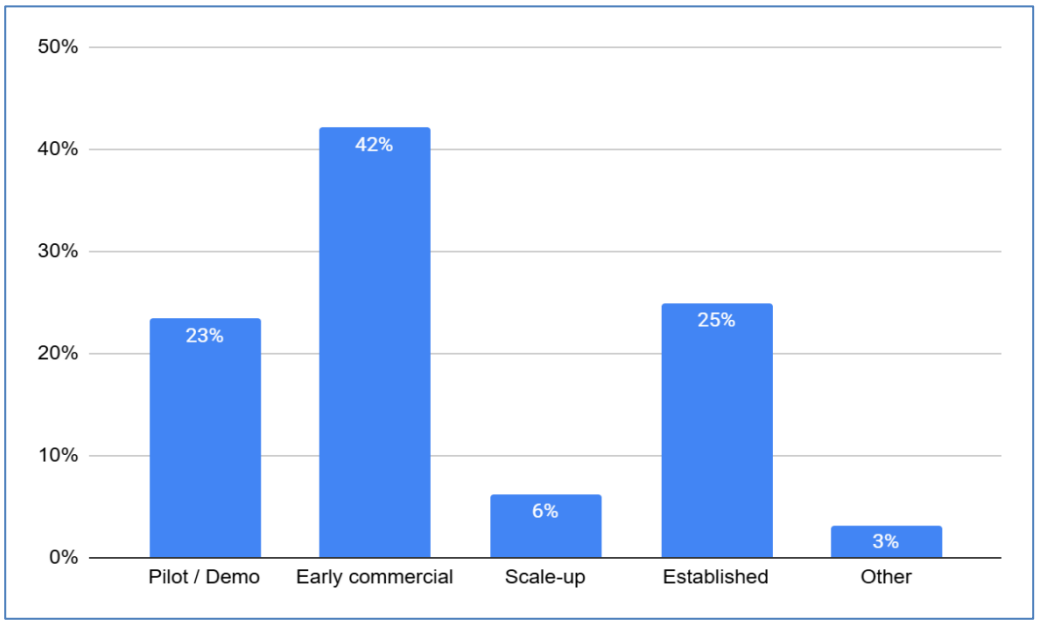


Figure 63: Phase of the current Swiss CMA in the DeCIRRA desk research list (own illustration).

As Figure 64 shows, most activities are in BiCRS with a majority active in biochar (20). This also confirms Lagler's findings from his European studies (Lagler 2025).

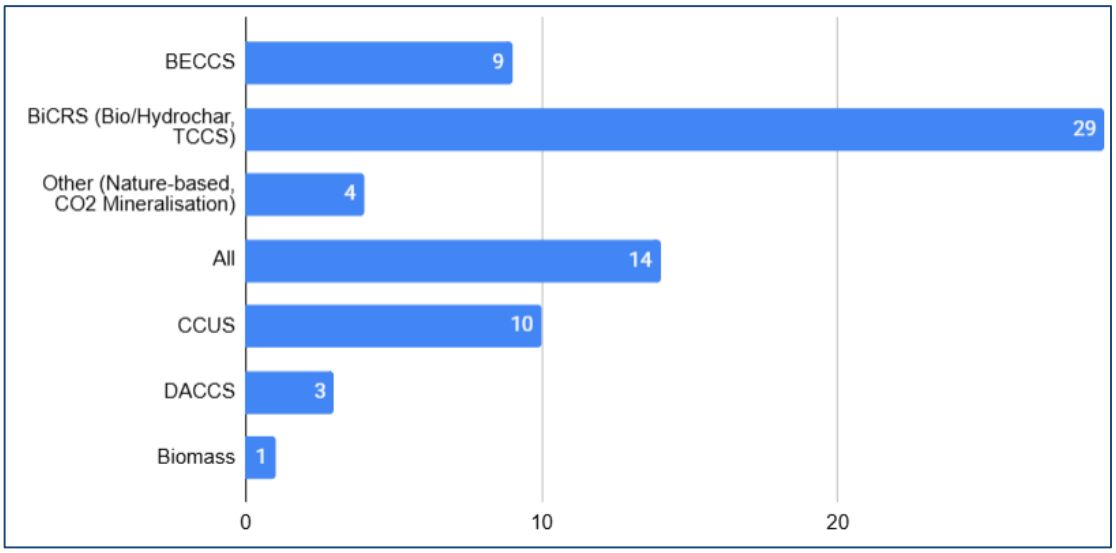


Figure 64: Technology landscape of the current Swiss CMA activities collected in the DeCIRRA desk research list (own illustration).

Figure 65 shows the distribution of the above identified key-activities amongst the CMA. As can be seen most are active in Tech Operations and Ecosystem & Advisory. Unsurprisingly, Biomass production is mostly carried out by BiCRS and BECCS companies; the exceptions at present are still CCUS projects utilising CO_2 from biogas. Financing is dominated by cross-technology players who, in addition to BiCRS, are also very active in the Carbon market and the Ecosystem & Advisory sectors. It will be important to follow the changes in Switzerland's CMA landscape as it continues to grow in scale.

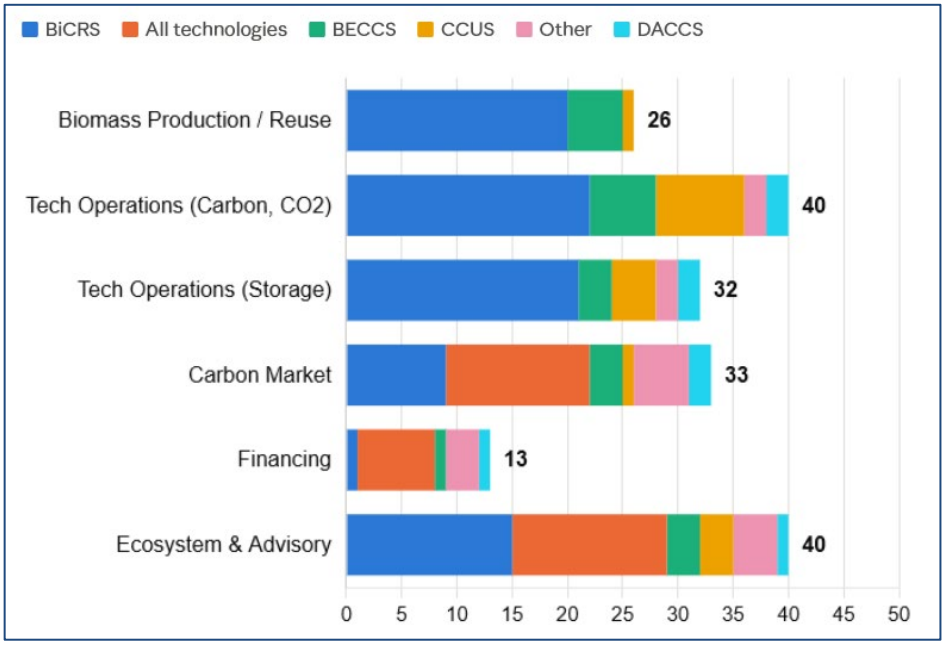


Figure 65: Number of Swiss CMA companies active in each key activity area by technology.

Note: Each horizontal bar represents one activity area; the coloured segments show how many companies engage in it per technology, and the number to the right of each bar is the total across all technologies. Companies working with more than one technology are counted once for each technology they are active in, so segment totals exceed the number of individual companies. To keep the technology breakdown readable, related sub-technologies were grouped as follows: BiCRS combines BiCRS, Biochar, Hydrochar, Biomass and TCCS; Other combines Nature-based solutions and CO_2 mineralisation; CCUS combines CCUS and CO_2 utilisation; All technologies covers companies whose activities are not tied to a specific technology but span the sector as a whole; BECCS and DACCS are shown as their own categories.

4 Optimal CMA mix and distributional impacts

4.1 Quantifying CMA mix for Switzerland in 4 scenarios in 2050

After introducing the role of each CMA in the respective sections, this section presents selected quantitative comparisons across our four scenarios, covering marginal avoidance costs, storage types, gaseous CO_2 capture sources, and handling. We compare results from the scenario report (Guidati et al. 2024) with the updated modelling described in Section 1.5.

Marginal Avoidance Costs: Marginal avoidance costs reflect the cost of eliminating the last tonne of CO_2 in a given scenario. They should not be confused with total avoidance costs (area under the curve): because the marginal cost curve can be steep at the end, reflecting that the last required tonnes avoided may be disproportionately expensive – particularly where low-cost CO_2 transport and storage infrastructure is unavailable.

As displayed in Figure 66, under the Octopus and Butterfly scenarios, marginal CO_2 avoidance costs reach approximately CHF 190–225/t in the updated modelling and CHF 200–250/t in the original scenario report, broadly consistent with the assumed pipeline cost. Under the Clam scenario, costs rise sharply to above CHF 1,480/t (updated) or CHF 1,280/t (original), and remain elevated under the Snail narrative at around CHF 550/t and CHF 530/t respectively. See Table 2 for a full overview of model assumptions.

In summary, the "alone & conservative" approach represented by the Clam scenario leads to a dramatic increase in marginal CO_2 avoidance costs and may put Switzerland's 2050 net-zero target at risk, as costs at this level are unlikely to be supported by the public. This points towards the need for building a pipeline that connects Switzerland to an expected European CO_2 transport network in order to keep the costs of decarbonisation as low as possible.

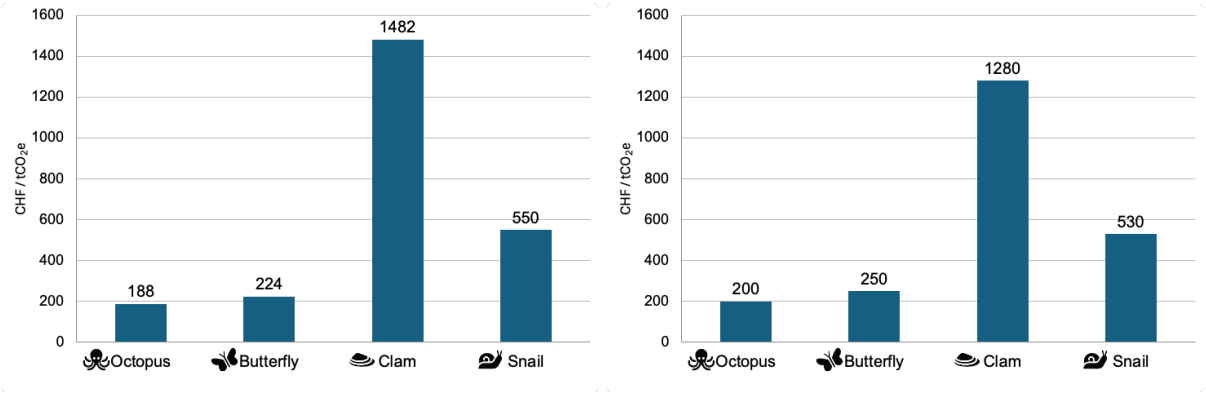


Figure 66: Marginal CO_2 avoidance costs in 2050 under the four scenarios (left new / right old).

Optimal CO_2 storage composition: As shown in Figure 67, from a volume perspective storage as gaseous CO_2 is the most attractive carbon disposal option even in the Clam scenario where cost of transport and storage are very high. Storage as wood (timber in construction) is part of the optimal solution under all four narratives, meaning that this is a low-cost and attractive CO_2 capture option that needs to be incentivised. Storage as biochar is attractive as long as its co-benefits in terms of reducing N_2O emissions from agriculture (including from fertiliser use) are accounted for, and also when the costs of storage of gaseous CO_2 rise. In addition, storage of solid carbon in the subsurface as hydrochar is also included in the updated model and becomes only attractive in scenarios with higher transport costs. This is because for hydrochar storage is costly, whereas biochar may receive a revenue due to its different application options. Note that the scenarios vary in the total amount of removal needed, as in the Octopus and Snail scenarios 6 Mt CO_2e per year are bought as international offsets. Therefore, the overall storage need in those scenarios is substantially lower.

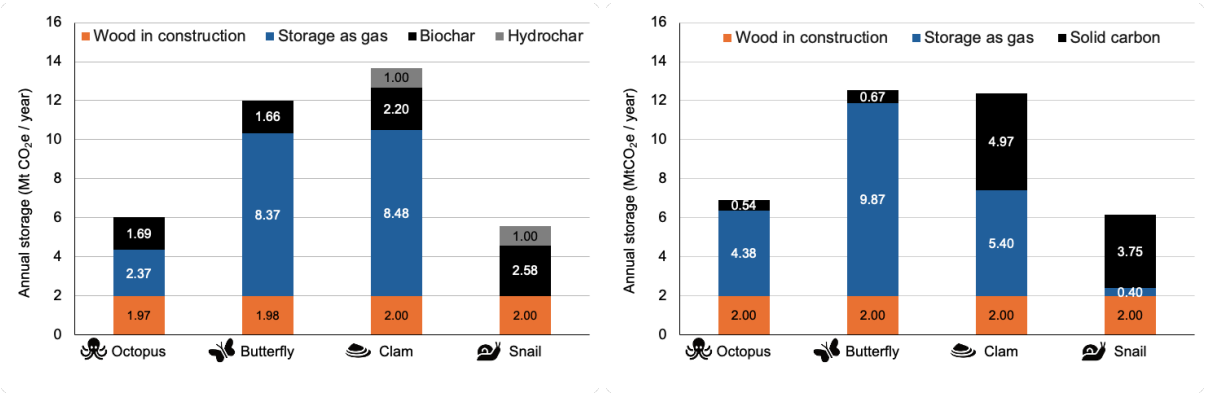


Figure 67: Optimal composition of CO_2 storage types in 2050 under the four scenarios (left new / right old).

Optimal gaseous CO_2 capture sources and handling: CO_2 capture from large point sources and from biogas production is an important technology under all scenarios, even though capture from large point sources was not optimal under the Snail narrative in the former modelling results because of the very high costs of CO_2 transport and storage (see Figure 68). This suggests that this is a no-regret technology that will need to be pursued in most potential futures. We can see, however, that a late start of efforts to enable cost-effective CO_2 transport and storage can be problematic as it keeps the overall costs high even in the longer-term. The only chance to keep overall costs low and the target in reach is then through a high share of compensation abroad or, in the Clam scenario's very extreme circumstances, to close down those installations that are not allowed to emit anymore and cannot acquire emission allowances.

Due to its high energy requirements, DAC within Switzerland was only in a very little amount optimal in the original Clam scenario but not anymore in the updated modelling. This suggests that DAC is not really an option for Switzerland given high costs and the limited national storage potential. In the Snail scenario there is no CO_2 storage in the updated modelling. Instead, CCU within Switzerland, including for SAF production, becomes optimal and there is even some CO_2 released back to the atmosphere, although much lower than in the former modelling. In the former modelling the share of CCU was much higher under the Clam scenario, which would have required a massive increase in electricity generation and the establishment of the necessary infrastructure to connect H_2 production sites with CO_2 capture sites. The costs of this infrastructure are not captured by the Swiss Energyscope model. Still, locally, CCU solutions may be possible, especially under the assumption of limited transport of electricity and/or hydrogen.

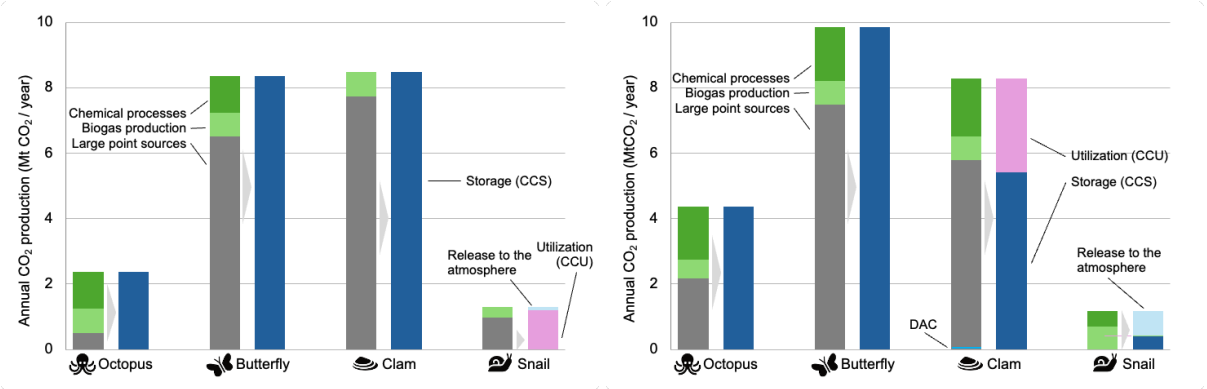


Figure 68: Optimal gaseous CO_2 capture sources and handling in 2050 under the four scenarios (left new / right old).

4.2 Economic impacts of Switzerland's net-zero target across DeCIRRA scenarios

The Energy system model analyses in the Scenario report (Guidati et al. 2024) provide insights on the optimal technological CMA mix for the net-zero transition, but energy system models' main measure for comparing the cost to society in different scenarios is energy system costs at constant levels of energy service provision. In order to also capture costs in terms of consumer welfare losses when demand and international trade react to increased energy costs, we linked the SES-ETH (a partial-equilibrium (PE) model) with the computable general equilibrium (CGE) model GEMENE of the Swiss economy. This allows us to quantify the wider economic consequences – effects on GDP, sectoral activity, consumer welfare, international trade –, and the distribution of policy costs across households (see Section 1.4.2 for more details on the methods). It should be noted that this analysis is based on the original results from the SES-ETH model published in the Scenario report (Guidati et al. 2024) (Figures 66, 67 and 68 right graphs) and do not incorporate the updates of the modelling results presented in this report (Figures 66, 67 and 68 left graphs).

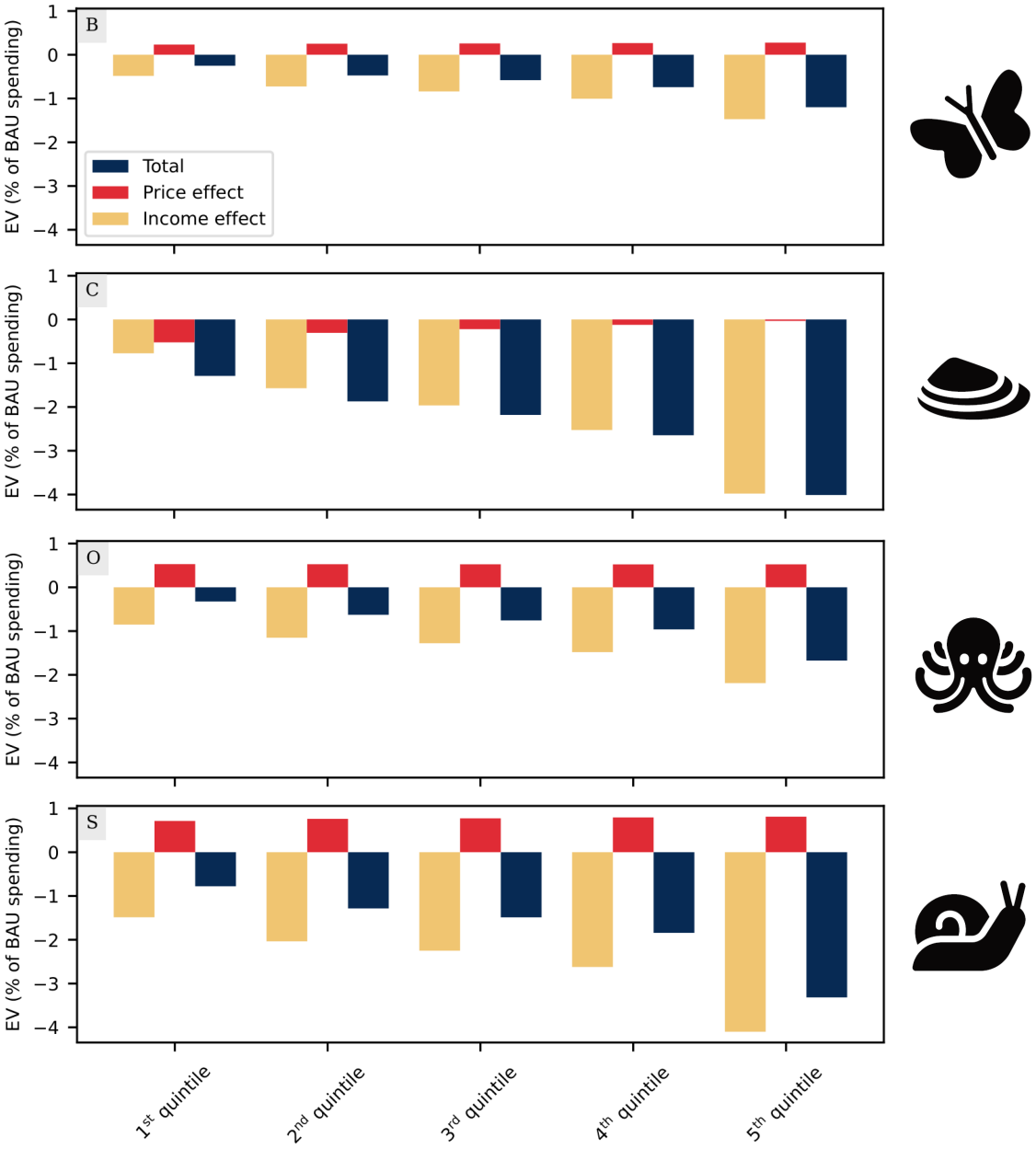


Figure 69: Change in consumer welfare measured as equivalent variation (EV) relative to BAU-spending. Consumer welfare impacts ("Total") are decomposed into uses side "Price effects" and sources side "Income effects".

Partial-equilibrium ranking of scenarios. In the bottom-up, partial-equilibrium (PE) view (see Figure 69), Butterfly is cheapest at CHF 3.14 bn, Octopus a close second at CHF 3.20 bn (by design: the offset price equals the marginal domestic abatement cost), Snail costs CHF 5.17 bn, and Clam is the most expensive at CHF 13.59 bn, driven in large parts by the high cost of strictly domestic CO_2 transport and storage.

General-equilibrium effects re-rank and amplify the cost. Demand responses lower the partial-equilibrium energy-system cost, but the foregone consumption has welfare costs elsewhere, and changes in input demand together with international trade flows shift Switzerland's terms of trade (ToT). Consumer-welfare losses in general equilibrium exceed the PE energy-system cost in every scenario except Clam, where the two happen to coincide. For Snail, the PE perspective underestimates the welfare cost by about CHF 5 bn – roughly half of the actual cost.

The Butterfly–Octopus comparison: a cautionary tale on offsets. Butterfly and Octopus share technology assumptions; they differ only in whether the last 6 Mt are abated domestically or bought abroad at the same marginal cost. PE would judge them equivalent if offsets abroad cost the same as domestic emission reductions. In GE, however, paying for offsets changes the balance of payments: Switzerland must give up imports, which increases equilibrium prices of imports through exchange rate effects, or increase exports which requires lowering their prices. Either way, Switzerland experiences a decrease in its ToT (which is a measure of the amount of real imports that can be afforded from a given amount of real exports). The resulting ToT loss is worth about CHF 1.2 bn (a 0.23% ToT change on CHF 527 bn of BAU exports), and consumer-welfare losses end up roughly 25% larger under Octopus than under Butterfly. For international offsets to be welfare-optimal, they would have to be markedly cheaper (CHF 140/tCO_2 in our scenarios) than domestic marginal abatement (CHF 220/tCO_2). If Switzerland is relying on international offsets, it is therefore making a bet on international offsets being about 36% less expensive than domestic emissions reductions.

The Snail cautionary tale. In PE the Snail energy-system cost is about 65% higher than Butterfly; in GE the welfare cost is more than 2.5 times as high. Treating offsets as a reason not to invest in human capital and infrastructure (the Snail world) is therefore far more damaging than the bottom-up view suggests.

GDP and household distribution. GDP losses are driven mainly by lower value added in Services and Real Estate, and to a lesser extent in Gas distribution, Construction, Agriculture and Non-metallic minerals. Energy goods become more expensive but many non-energy goods (notably Services) become slightly cheaper; for the average consumer the two price effects roughly offset each other, and the welfare loss is driven by lower wages and capital rents. Under command-and-control regulation, the distribution of policy costs across the five income quintiles is progressive in every scenario: high-income households rely more on wage and capital income, both of which decline. Figure 70 illustrates how passing CCS costs to consumers via waste fees makes the price-side effect more regressive and the income-side effect less progressive in all scenarios except Snail (which does not deploy CCS in waste incineration). Financing international offsets (Octopus, Snail) through an agricultural goods tax likewise hurts low-income households on the price side and benefits high-income households more on the income side.

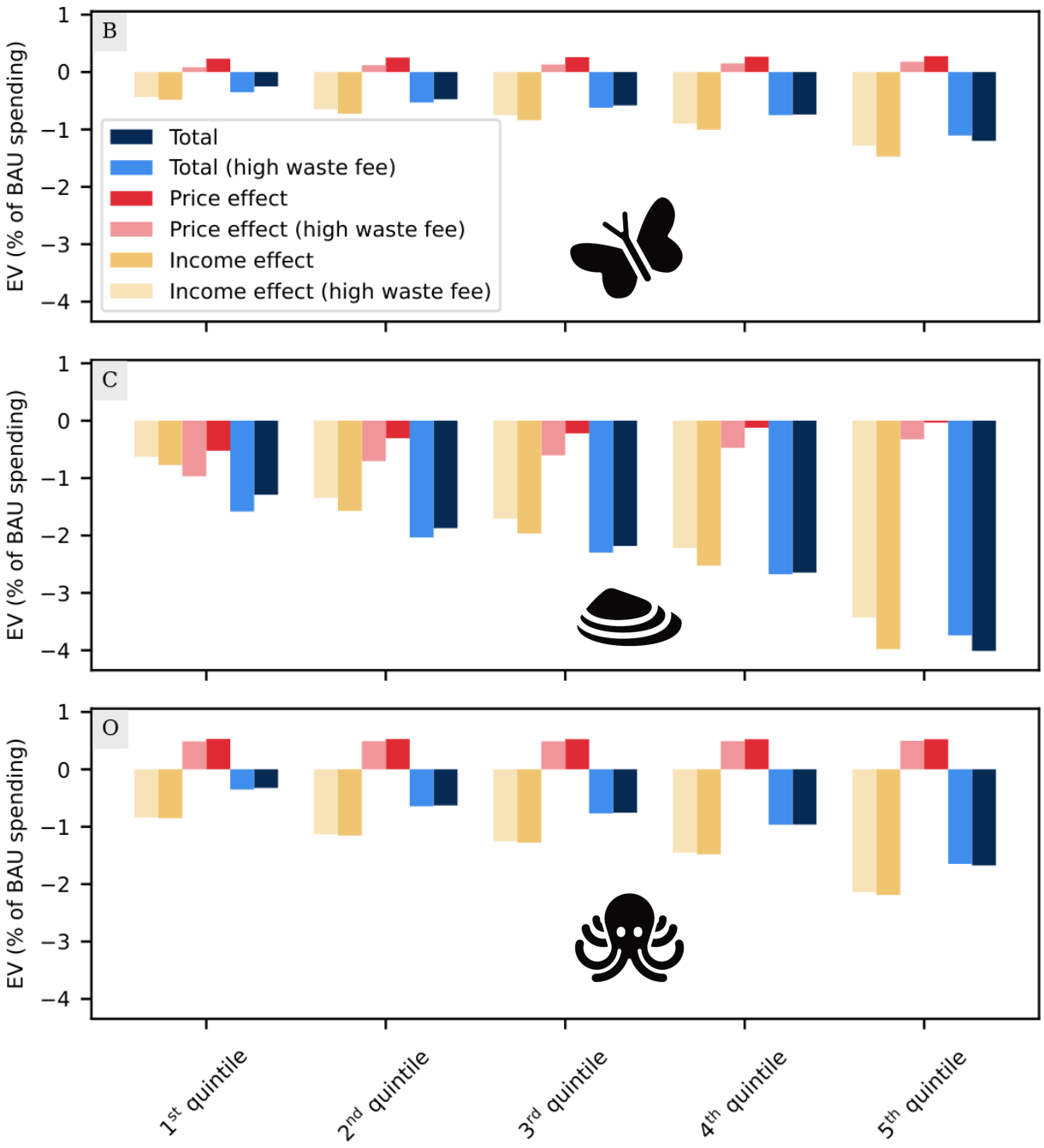


Figure 70: Change in consumer welfare measured as equivalent variation (EV) relative to BAU-spending assuming pure command-and-control policies (dark colours*) or financing CCS in* ***waste incineration*** *through waste disposal fees (light* colours*). Consumer welfare impacts ("Total") are decomposed into uses side "Price effects" and sources side "Income effects".*

In summary, three implications follow for policy makers: First, an active strategy combining innovation, international cooperation, and domestic abatement (the Butterfly world) is the most beneficial of the four narratives; reaching it requires sustained investment in R&D and infrastructure. Second, international offsets should be treated with caution: their general-equilibrium cost exceeds their headline price, and their availability at scale by 2050 is not assured. Third, distributional design matters: mandated technology standards yield a progressive incidence across income groups, while pricing schemes that target waste fees or food prices erode progressivity to some extent.

5 Discussion

In this section we answer the research questions posed in the DeCIRRA project (see Section 1.2).

5.1 Q1: What would be the most efficient combination of CMA and the optimal timing of investments?

This question was answered through scenarios modelled with the Swiss Energyscope model (see Section 4), though several limitations must be kept in mind when interpreting the results. The model does not capture infrastructure and geographical differences in detail and optimises a single target year rather than modelling transition pathways. It assumes that all gas transport infrastructure (e.g. for CH_4, CO_2, H_2) is simultaneously available everywhere. Transport infrastructure costs were modelled explicitly only for CO_2, and varying across scenarios. Most identified co-benefits and co-risks have not been quantified and included in the modelling. Validating the derived recommendations and identifying the optimal pathway toward them will therefore require additional regionally resolved models that also account for infrastructure availability and related costs.

5.1.1 Efficient combination of the four CMAs

Timber in construction (**TCCS**) is the first-priority option across all scenarios analysed, reaching its maximum potential of around 2 Mt CO_2/year in each case. This reflects the technology's commercial maturity, its cost-effectiveness relative to other approaches, and the absence of the infrastructure dependencies that constrain gaseous carbon management options. TCCS is deployable today and should be treated as the anchor of any Swiss carbon management portfolio.

Biochar is also always part of the optimal mix, with quantities varying from 1.66 Mt CO_2/year in the Butterfly scenario to 2.58 Mt CO_2/year in the Snail scenario. Together with TCCS, biochar constitutes a no-regret cluster of options that delivers abatement benefits under a wide range of future scenarios without depending on CO_2 infrastructure. Both are commercially ready technologies at TRL 9, yet both remain constrained by regulatory gaps rather than technological immaturity. **Hydrochar** is only deployed in the Clam and Snail scenarios at 1 Mt CO_2/year.

Domestic Direct Air Capture (DAC) is not part of the optimal mix in any of the updated scenarios. Switzerland's constrained national renewable energy base means that allocating scarce clean electricity to DAC is not cost-efficient compared to using it elsewhere in the energy system.

Domestic carbon utilisation (**CCU**) in the form of e-SAF or e-methane is only economically rational in the Snail scenario.

The optimal mix depends heavily on whether **international offsets** are available. If international offsets are not available (Butterfly and Clam scenarios), gaseous CO_2 capture from large point sources like waste incineration plants, cement producers, and chemical industry becomes the dominant carbon management approach. Captured CO_2 is transported and stored outside Switzerland, most likely offshore. Marginal costs, however, differ by more than a factor of six between the two scenarios, at CHF 224/tCO_2e in Butterfly compared with CHF 1,482/tCO_2e in Clam, reflecting the impact of the **CO_2 transport infrastructure costs** assumed for these scenarios. If Switzerland can use international offsets and international infrastructure remains accessible only at very high prices (Snail scenario), biochar, TCCS and hydrochar must take on a significantly larger share as substitutes for gaseous CO_2 storage.

5.1.2 Timing of investments

The report's central message on timing is unambiguous: early investment in **CO_2 transport infrastructure** is the most critical decision Switzerland faces in the near term. Delaying **access to international CO_2 storage** (the Clam path) increases marginal avoidance costs significantly and places the 2050 net-zero target at serious risk. The longer Switzerland waits to integrate into emerging European CO_2 infrastructure, the more expensive and difficult the transition becomes.

Establishing clear national and international investment frameworks for carbon management at the earliest opportunity will significantly reduce long-run abatement costs. Regulatory uncertainty is itself a cost driver: it raises the risk premium on private investment and delays deployment. Early commitment to stable regulatory conditions is therefore not merely administratively desirable but economically necessary.

The general equilibrium analysis adds an important nuance on offsets. While buying foreign offsets (Octopus) or full domestic abatement (Butterfly) appear almost equivalent with regard of the marginal avoidance costs in a cost-minimisation model, the general equilibrium model reveals that foreign offsets worsen Switzerland's terms of trade meaning that the economy as a whole is worse off even though the cost-minimisation calculation looks identical (unless foreign offsets are substantially cheaper than domestic avoidance). The Butterfly scenario, which achieves domestic abatement via international pipeline access, is economically preferable once these macroeconomic effects are accounted for. This finding strengthens the case for **prioritising domestic and pipeline-connected abatement and removal over the purchase of international offsets in the situation where international offsets are not substantially cheaper** compared to domestic ones. Thus, it also has direct implications for how Switzerland structures its future National Determined Contributions and Article 6 strategy under the Paris Agreement.

5.2 Q2: Which stakeholders need to be involved for successful implementation of CMAs?

Across virtually all four carbon management approaches analysed, a commercial business case does not exist without regulatory intervention. Unlike conventional energy technologies where cost reductions or the production of valuable energy eventually generates self-sustaining markets of a private good, carbon removal and capture services produce a public good (atmospheric CO_2 avoidance or removal) whose investment must be incentivised by policy. The business model analysis identifies a ***triple market failure*** affecting most CMA: little integration in compliance markets yet, missing CO_2 transport and storage infrastructure, and missing of agreed standards for certification for some CMAs. This confirms that regulation is essential: it turns a technically feasible technology like biochar into an investable one. The regulator is therefore not one stakeholder among many but the actor whose decisions determine whether a CMA ecosystem can form at all.

Scaling the market for CMA depends not only on the regulator but on a coordinated co-evolution of complementary actors. The contributions of suppliers of technology and feedstock, certification bodies, investors, and demand-side buyers from compliance or voluntary carbon markets are interdependent. Where one function fails, for instance where legitimation is absent because a technology lacks a legal category, or where market formation fails because no compliance demand exists, the entire ecosystem stalls regardless of the maturity of the underlying technology. Biochar and hydrochar are the clearest illustrations: both are commercially ready but remain constrained by regulatory gaps.

Optimising biomass allocation for BECCS, biochar, and TCCS requires close coordination among forest owners, regional forest cooperatives, associations, district foresters, cantonal forest services, WSL, and FOEN, since these actors need to work together to make Swiss forests resilient against negative impacts from climate change like more often and more severe droughts, fires, bark beetle damages, and storms reducing growth and stability. Methods like climate smart forestry guided by the Federal Forest Act (FoA), the CO_2 Act, and coordinated cantonal implementation, could be one important approach to securing Swiss wood biomass for these CMA.

In the following the ecosystem for each CMA is further described.

5.2.1 Biochar and hydrochar

For biochar and hydrochar, several **federal administrations** must work together. FOEN, the Federal Office for Agriculture (FOAG), and the Soil Protection Working Group on Intervention Values and Risk Assessment (AGIR) of Cercle Sol are the key partners for developing the regulatory framework for biochar application in agriculture. FOAG sets the fertiliser and soil protection standards that govern biochar use on agricultural land, while AGIR provides the scientific risk assessment methodology needed to establish safe application thresholds. There are also other barriers such as the requirements for removals – excluding construction material - to be entered into the land registry (Art. 8a CO_2 Ordinance), or the classification of hydrochar as waste under the Waste Ordinance and the restrictive application limits for biochar in agriculture continue to prevent the market from scaling.

Research institutions like ETH Zurich, ZHAW, Agroscope, FiBL, WSL, and HES-SO are the actors best placed to resolve scientific questions on soil impacts and carbon permanence that underpin more permissive regulation.

Public acceptance is not a deployment bottleneck for biochar or hydrochar. The DeCIRRA survey found that Swiss citizens are substantially more comfortable with solid carbon storage than with

geological CO_2 injection, and social acceptance should not be treated as a deployment risk for these technologies.

As **feedstock supplier**, wastewater treatment plants are the natural partners for hydrochar: sewage sludge is an abundant and consistent wet biomass feedstock, and hydrothermal carbonisation offers these plants a solution to their own waste management problem, creating a double incentive for cooperation. The agricultural sector (manure, slurry) and municipal organic waste streams represent additional feedstock sources, pending regulatory authorisation. For biochar, the forestry sector is the primary source: forest residues, low-grade wood, and landscape maintenance wood, supplemented by sawmill waste and agricultural crop residues. The main supply constraint is competition with the wood chip heating market, which currently absorbs most available woody biomass under long-term contracts.

Municipal utilities are emerging as a new category of biochar producer, integrating pyrolysis units alongside their existing wood energy and district heating operations rather than treating biochar as a separate business line. IWB in Basel is an example of this trend, converting regional green waste and landscape management wood to co-produce biochar as a by-product of heat and power generation. This pathway could meaningfully expand supply beyond forestry residues, but it also shifts the bottleneck downstream: if utilities scale up production, the current buyer base will not be sufficient to absorb the added volume, making the development of additional buyers and off-take agreements a precondition for this production pathway to scale.

A parallel, more distributed supply channel is emerging from startups like **Pyronet**, which deploy small scale pyrolysis heating systems for larger residential and commercial buildings, co-producing biochar directly alongside local heat.

On the **demand side**, farmers and their associations are the primary end-users of biochar in soil applications. For hydrochar specifically, the construction industry is an emerging channel, with companies such as Kohlenkraft and KLARK/LOGBAU pioneering the use of biogenic char as a concrete additive and offering an alternative where agricultural regulatory hurdles remain high. Certificate demand currently comes almost exclusively from the voluntary carbon market: not a single biochar project has yet been accredited under the Swiss compliance schem. Certificate marketplace operators – myClimate, South Pole/Airfix – connect producers to buyers, but their effectiveness depends on a recognised legal framework for the underlying removal activity.

As **cities** need to redesign infrastructure to become more climate resilient (Schwammstädte/sponge cities), biogenic char could be used at scale in structural soil substrates for street trees, stormwater retention systems, and other green infrastructure, where their water holding capacity and soil enhancing properties directly support urban water management goals. The company Swiss Biochar is already producing biochar for this target market.

5.2.2 Timber Carbon Capture & Storage (TCCS)

The Federal Office of the Environment (**FOEN**) actively supports timber construction through its Forestry Department and the Wood Action Plan, and the 2015 revision of the Fire Protection Ordinance already allows timber construction across all building categories.

The regulated Swiss sink market ("**Senke Schweizer Holz**") has operated since 2014 years and has created large amounts of credits which were sold to the transport sector. The approach is incompatible with the EU Carbon Removal Certification Framework (CRCF) and Paris Agreement Article 6.

Public acceptance is not a deployment barrier. Switzerland already leads globally with a timber construction share of approximately 15%, reflecting decades of established practice. Forest managers, sawmills, and manufacturers of engineered wood products form a well-established supply chain of SMEs with long generational histories. Scaling is primarily a question of market development and investment – particularly in sawmill capacity – rather than technology development.

WSL is the primary **research** actor developing and analysing forest management scenarios that inform supply planning. Empa and University of Applied Sciences Bern are training specialists across the full value chain – from forest management through to timber construction. They need to ensure that experts are trained in sufficient numbers to meet growing demand.

Lignum is the sector's central knowledge diffusion actor. **Networks** such as the Swiss Wood Innovation Network (S-WIN) or SVUT are important complementors. TimberCarbon and equivalent voluntary market operators are already handling or preparing to handle certificate issuance and trading.

On the **demand side**, public procurement is the most direct lever available without new subsidy instruments: the Forest Act already obliges the federal government to promote Swiss timber in federal buildings, and cantonal authorities such as the City of Zurich are introducing mandatory green building standards. The KliK Foundation is the principal buyer on the regulated side, purchasing sink certificates to fulfil fuel importers' compensation obligations.

5.2.3 Bioenergy with Carbon Capture (BECC)

BECC has a complex **regulatory** landscape because FOEN and SFOE must jointly coordinate: FOEN oversees climate and waste policy, while SFOE is responsible for energy security and must consider the impact of CO_2 capture on electricity production from biomass and waste incineration plants. Their joint coordination is a precondition for any investment decision by large point source emitters.

Waste incineration plants – 29 KVA operators organised under VBSA – are the largest and most concentrated point sources and were ranked by NET actors surveyed as the most important emitter group after the federal offices. KVA Linth in Niederurnen has been selected as the first implementation site under the VBSA sector agreement and the ZAR competence centre CO2. **Cement plants**, organised by cemsuisse, are the other major emitter group, with unavoidable process emissions making CCS their primary decarbonisation route. Agricultural biogas operators and wood CHP plants represent a third source category. Regionalwerke Baden AG leads the first BECCS project to receive ITINERO funding, announced in March 2026 – a reference project whose experience will inform subsequent deployments.

Empa, EPFL, and PSI are **researching** new capture materials and processes. The Swiss Carbon Removal Platform provides the main coordination and communication function across the BECCS actor network. Certificate marketplace operators and the financial industry are needed to structure project financing, though the report notes these connections are not yet sufficiently established for capital-intensive CCS projects.

Demand: Neither the Swiss ETS nor the EU ETS currently credits negative emissions, meaning there is no compliance demand for BECCS certificates. The EU Commission’s EU ETS revision proposal envisages limited centralised purchases of BioCCS removals from 2031 onward, which would turn it into a central market player on the demand side. The voluntary carbon market is the only existing revenue channel, but it is insufficient to justify the capital-intensive investments required.

5.2.4 Direct Air Carbon Capture (DACC)

No specific policy framework for DAC exists in Switzerland. SFOE is a critical **regulatory actor** not only for climate reasons but because DAC's substantial electricity and heat requirements make it an energy security question: any large-scale Swiss deployment would need to be integrated into energy system planning. The Federal Council's late 2025 consultation on the federal administration's own net-zero target for 2040 is a first signal that public procurement of DAC services may become a near-term demand instrument without requiring new legislative frameworks.

Climeworks is Switzerland's (and the world's) – most advanced **technology provider** and DAC operator, making it a globally unique asset in the Swiss innovation ecosystem. Its Mammoth plant in Iceland is the first commercial-scale facility providing real-world data on modularity, capacity factors, and learning curve dynamics.

ETH Zurich, PSI, and Empa are the domestic **research** actors working on next-generation sorbent materials and process integration. Internationally, solid sorbent DAC (Climeworks) and liquid solvent DAC (Carbon Engineering/1PointFive, operating the STRATOS plant in Texas) are the two competing approaches at scale. These global players are relevant as technology benchmarks and potential licensors.

Demand: The voluntary carbon market currently provides DAC's only revenue stream. Stakeholders consistently identify public CDR procurement – federal and cantonal governments committing to purchase certified Swiss DAC removal volumes – as the highest-impact near-term measure available. The EU Commission’s EU ETS revision proposal of limited centralised purchases of DACCS removals from 2031 onward opens a path in this direction. The US remains the most active public demand market globally, with US$ 3.5 billion allocated for Regional DAC Hubs – context directly relevant to Swiss actors including Climeworks, whose scaling depends on markets moving faster than Switzerland on public demand creation.

5.2.5 CO_2 transport and storage infrastructure

CO_2 transport infrastructure is the enabling backbone on which BECCS/BioCCS and DACCS depend. The chicken-and-egg problem – capture technology providers cannot invest without committed transport capacity, and infrastructure operators cannot invest without committed emitters – means that no market mechanism alone can initiate construction. This makes the **federal government** not merely an enabling actor but the indispensable **coordinator** without whom the ecosystem cannot form.

The forthcoming CCS framework act, due to Parliament by end of 2026 and expected to enter into force in 2031, is designed to give the federal government a clear mandate over the planning, approval, and financing support of CO_2 transport infrastructure – currently a gap, since pipeline permitting authority rests with the **cantons** individually. Federal-cantonal alignment is therefore a precondition for any coherent routing plan.

There are mainly two national players assessing building and operating a national CO_2 transport infrastructure: **The CO_2 Pipeline Schweiz AG**, founded in 2025, as well as a **group of regional gas companies**. The **oil industry** is an essential partner too as when fossil pipelines are decommissioned, their repurposing offers both a cost advantage and significantly higher public acceptance compared to new construction. **ChemOil** (a subsidiary of SBB) covers smaller-scale and pilot-phase transport.

Because Switzerland has limited domestic geological storage capacity, cross-border transport is critical. **Norway** is the primary partner: the Northern Lights project is the world's first open-access third-party CO_2 transport and storage facility, and Switzerland has concluded a bilateral agreement covering cross-border CCS cooperation. **Germany** (**OGE** is developing a 1,000 km CO_2 transport network) and **France** are key transit countries to storage sites in Norway, **Denmark, and the Netherlands**. To avoid strategic vulnerability from dependence on a single partner, Switzerland should develop domestic storage capacity alongside agreements with multiple international partners.

Geological storage is the terminal link in the CCS chain and the one on which Switzerland is most dependent on others. Without confirmed access to permanent storage – domestic or abroad – no investment in capture or transport infrastructure can be fully de-risked. The forthcoming CCS framework act must establish rules for site selection, permitting, operation, monitoring, and long-term liability. **Swisstopo's** 3D geological data from the Swiss Plateau, combined with **NAGRA's** deep drilling data, provides the empirical basis for any domestic storage assessment. The CITru pilot project, led by ETH Zurich under the SWEET ACHIEVE project, is testing CO_2 injection in a saline aquifer in Trüllikon (Canton Zurich) and will generate the first real Swiss subsurface data. Long-term liability for geological storage extends beyond any conventional investment cycle, potentially to centuries, making pure private financing untenable without explicit state backstop mechanisms.

Overall, this analysis shows that the depth of the ecosystem differs across CMAs. Future research could build on this by conducting a comparative analysis of CMA actor network structures across European countries, identifying effective coordination models and assessing their replicability for Switzerland.

5.3 Q3: Which accounting and implementation frameworks exist and what amendments are needed?

Three distinct forms of accounting are relevant for CMA investment incentives and must be kept analytically separate:

- **life cycle assessment (LCA)**, which quantifies material and emissions flows along the value chain;
- **national GHG inventory accounting** under the Paris Agreement based on IPCC guidelines, which determines what Switzerland can claim toward its national targets;
- **project-level carbon market accounting**, which sets baselines, additionality requirements, and MRV rules governing whether certificates can be issued and traded.

These approaches have different merits and are frequently conflated, creating confusion in policy debates.

The IPCC Task Force on National Greenhouse Gas Inventories has been mandated to deliver a methodology report on CDR, CCS, and CCU by end-2027, which is expected to provide additional guidance on reporting removals from these methods under the UNFCCC.

Until then, significant gaps remain: project-level approaches such as those developed by Neustark – where mineralisation technology permanently binds CO_2 into recycled concrete – form the basis for

voluntary market credits, but Switzerland currently cannot integrate these into the compliance market because the absence of approved inventory guidance prevents their reporting in the national GHG inventory.

The central contested issue in accounting – in Switzerland and internationally – concerns a fundamental asymmetry: fossil CO_2 emissions warm the atmosphere for millennia, yet most available CMA, especially nature-based approaches such as biochar and TCCS, store carbon for shorter periods.

Four accounting approaches are currently debated for addressing this asymmetry, and no consensus has yet emerged: the *inventory approach* (used in Switzerland's HWP Pool); *project-level accounting* as applied in voluntary carbon markets; the *geological-only approach* of the EU ETS, which restricts eligibility to geological storage and mineralisation on the grounds of true equivalence with fossil emissions; and the *like-for-like approach*, which argues that shorter-duration storage (e.g. TCCS) may legitimately offset methane emissions with shorter atmospheric lifetimes.

5.3.1 Accounting for TCCS

Within the DeCIRRA project, three accounting approaches were examined for TCCS, each with distinct advantages and limitations.

1. The **value chain approach** traces carbon flows from forest through processing to the final built structure, is compatible with national GHG inventories and enables precise attribution of climate performance. However, establishing a credible baseline is complex and the involvement of multiple stakeholders increases administrative burden.
2. The **Harvested Wood Products (HWP) Pool approach** underpins Switzerland's regulated CO_2 market ("Senke Schweizer Holz"), applying the same inflow-outflow logic as the national GHG inventory. It has operated since 2014, but it has been criticised with regards to baseline setting, the implementation of additionality and handling of durability/outflow management (see Section 2.3.9).
3. The **project-level (building) approach** quantifies biogenic carbon stored in a specific building and is the dominant model in voluntary carbon markets, enabling internationally tradable units and creating direct incentives for developers and investors, but requiring robust reversal monitoring, credible building-level baselines, and mechanisms to address permanence and end-of-life liability.

Since each of these approaches involves trade-offs, there is no consensus on which of those approaches should be supported in the long-run. Since they are not only the basis for accounting but also for issuing credits and thus have financial and distributional impacts, the discussion is very contested. The three options listed above were discussed within the DeCIRRA project that merit closer assessment. For the value chain approach proposed by Swiss Post too little detail was available at the time of writing to assess it here.

The major problems to be addressed for HWP pool approach are baseline and additionality critiques and shifting demand for credits from fuel importers to the agricultural sector's methane emissions, implementing the like-for-like approach. This preserves compatibility with the current national inventory and avoids the need for new regulation but keeps Switzerland nationally confined and incompatible with EU frameworks.

The project-level approach is requiring revision of the durability definition, establishment of end-of-life liability rules (such as transfer of liability to a national fund), and creation of a unified, highly transparent registry. A transition period during which the object-based approach gradually displaces the current pool approach would be necessary. The rules should take into account Art. 6 and EU CRCF methodologies.

A particularly important dimension of **double-counting** concerns the substitution effect – emission reductions achieved by substituting cement with timber construction. In a voluntary market context where certificates offset Scope 2 or 3 emissions, this is unproblematic. However, if substitution certificates are sold and accounted for under Article 6.2 of the Paris Agreement, Switzerland would be obligated to make a corresponding adjustment, achieving no net reduction. And if EU rules were to change to allow such certificates in the EU ETS, double counting would arise at the system level, since cement production is already covered by the ETS cap. In the current Commission proposal (2026/0212), no certificates for TCCS can enter the EU ETS market.

5.3.2 Accounting for BECCS and DACCS

For BECCS and DACCS, no Swiss accounting standards currently exist. The Swiss CCS framework act under preparation must establish monitoring, reporting, and liability rules for transport and geological storage, including requirements addressing non-permanence, leakage, and double counting – for example in cases where wood is used in a cascade before eventually being used in an energy recovery application with CCS. Switzerland's 30-year permanence requirement is internationally out of step. This gap must be addressed in the CCS framework act.

5.4 Q4: Which policies and revenue streams are available and what gaps exist?

A stakeholder survey of approximately 140 actors across the CMA ecosystem revealed broad consensus that a CO_2 price – whether through a levy or an emissions trading system – is the key policy instrument for advancing CMA in Switzerland. This was favoured above all by technology manufacturers. In second place were binding targets, favoured particularly by regulators. Tax credits were rated as less attractive than expected given their central role in US and Canadian climate policy. Other important funding instruments mentioned in workshops include subsidies for research, pilot, and demonstration projects. Carbon Contracts for Difference were not systematically rated in the survey but were consistently identified in interviews as the most appropriate scaling instrument for capital-intensive technologies such as DACCS and BECCS, where carbon prices may not be enough.

Business models for CMA are structurally dependent on credible, long-term regulatory frameworks, since they typically produce no marketable product – atmospheric CO_2 removal is a public good whose value must be assigned by policy. Where the market is internationally open, it will tend to select and finance the cheapest available options. This could mean that low-cost approaches such as ocean alkalinity enhancement set the price floor for removals in international carbon markets, potentially crowding out more expensive but domestically strategic options. Policymakers must therefore consider whether a purely market-driven instrument achieves the desired portfolio of removal approaches, or whether complementary mechanisms – such as technology-specific support, domestic content requirements, or capacity procurement – are needed to ensure a resilient and diversified carbon management sector.

5.4.1 Current policies and gaps by technology

TCCS: The KliK Foundation provides regulated demand through the "Senke Schweizer Holz" scheme, making TCCS currently the only CMA with any compliance market revenue in Switzerland. However, there are some structural problems such as determining the most likely reference scenario and additionality as well as the current credit demand coming from fuel importers rather than hard-to-abate sectors. As embodied emission limits in building standards through the SIA 390/1 become stricter, the scope for additionality in TCCS narrows, directly affecting the business case for certificate providers. Future research should therefore develop a framework that sequences and adapts the policy mix over time, matching it to the evolving state of market development.

Biochar: The voluntary carbon market remains the only revenue channel in practice, even though the Swiss CO_2 Act would in principle permit biochar projects to be credited under the compliance scheme: to date not a single project has been accredited. Regulatory barriers are the reason – the classification of hydrochar as waste and the restrictive limits on agricultural application of biochar – and they block both compliance-market demand and the scaling of production. The Swiss Biochar Research Network, Charnet, myClimate and South Pole/Airfix provide market coordination and certificate infrastructure, but their effectiveness is limited if the underlying removal activity lacks a recognised legal framework.

BECCS: No compliance demand exists in the Swiss or EU ETS yet, but with the EU ETS reform this is likely to change, given that the Commission's ETS revision proposal from July 2026 envisages centralised purchases of BioCCS removal units managed by the Commission.

DACCS: The voluntary carbon market and the VCS DAC module (VMD0056) provide the only current revenue stream in Switzerland. Public CDR procurement – federal and cantonal governments committing to purchase certified Swiss DAC removal volumes – is identified as the highest-impact near-term measure without new legislation. Such a purchase scheme would be introduced in the EU ETS if the Commission's revision proposal from July 2026 is adopted. CCfD instruments are an appropriate scaling mechanism given DAC's capital intensity and long revenue timelines but are not yet available in Switzerland. SFOE's demonstration funding programme was previously an important support instrument and its reinstatement with CMA-specific funding streams is identified as a priority gap.

CO_2 transport and storage: The forthcoming CCS framework act is the central policy gap. Until it enters into force (expected 2031), there is no federal mandate over CO_2 pipeline planning and permitting, creating fragmentation across cantons. EU PCI project status and the Innovation Fund are the most significant external financing instruments for infrastructure with cross-border relevance. The bilateral agreement with Norway is the most substantive international step taken to date, but to avoid strategic vulnerability Switzerland must develop domestic storage capacity alongside agreements with multiple international partners. The concept of a national fund or public authority assuming long-term storage liability after a defined period of demonstrated integrity – analogous to the German approach or NAGRA's model for nuclear waste – merits serious consideration.

5.5 Q5: How will co-benefits, external costs, and risk reduction approaches be considered?

Co-benefits and risks were identified for all four technologies and the associated infrastructure. These are summarised below and should be systematically incorporated into investment analysis and policy design, both because they affect the net social value of each approach and because they influence public acceptance and regulatory feasibility.

5.5.1 Co-benefits

Biochar: Climate-relevant co-benefits include reduction of N_2O emissions from soils, enhanced carbon storage due to microbial stimulation, and reduction of methane from sewage plants, manure, cattle, and rice cultivation. Further co-benefits include enhanced plant growth through improved water retention and root development, reduction of malodorous compounds and microplastics in treated substrates, potential use as a concrete additive, and enhanced feeding stuff uptake in animal husbandry. Swiss soils have lost significant organic material – in some cases up to 78% – over centuries of agricultural use; biochar represents a potential means of regenerating soils while simultaneously storing carbon, and these co-benefits are important both for reducing net costs (through saleable by-products) and for increasing social and regulatory acceptance.

TCCS: Co-benefits include enhanced tree growth through Climate Smart Forestry, improved climate resilience of forests, the establishment and safeguarding of climate-resilient high-value timber species that secure future wood supply and carbon storage potential, and reduced risk of carbon reversal due to disturbances such as wildfires, bark beetle outbreaks, storms and other climate-related forest calamities (buildings are better protected than standing wood). TCCS also enhances biodiversity in well-managed forests, reduces building material waste relative to conventional construction, and generates significant substitution effects by displacing steel and cement, two of the most emissions-intensive materials in the construction sector.

BECCS: BECCS provides a double systemic benefit: it generates electricity and heat (or synthetic fuels if captured CO_2 is used for PtX applications) alongside negative emission certificates. Higher CO_2 concentrations at point sources relative to the atmosphere mean lower energy demand per tonne captured compared to DAC. Better air quality results if other pollutants are captured alongside CO_2. CCU applications – producing synthetic fuels or industrial gases from captured CO_2 – reduce dependence on carbon imports and enhance industrial flexibility, with the feasibility of alternating between negative emissions and renewable hydrocarbon production depending on hydrogen availability making flexible plant design a key investment consideration.

DACCS: If DAC is co-located with a storage site, long-distance CO_2 transport may not be required, reducing energy needs for transportation. Better air quality if other pollutants are captured alongside CO_2. Industry becomes more independent and flexible, for example from carbon imports, if captured CO_2 is used to produce synthetic energy carriers.

5.5.2 Risks and external costs

Biochar: Risk of deforestation or overexploitation of forests through unsustainable raw material procurement. Improper pyrolysis processes or biochar utilisation can lead to release of harmful polycyclic aromatic hydrocarbons (PAHs) and other pollutants. Risk of stored carbon being released back into the atmosphere from soils. Lower crop yield is possible due to reduced soil fertility or nutrient availability through increased acid buffering in treated soils, and there are potentially ecotoxic effects. Negative effects on health through increased release of substances remain possible. Long-term studies for Swiss conditions are lacking, with FOEN and FOAG noting this gap in 2026.

TCCS: Risk of deforestation or overexploitation of forests if raw materials are not procured sustainably. This risk may be much higher for imported timber compared to national timber, as Swiss regulations guarantee high sustainability standards. In addition, climate change may reduce the future availability of high-value timber species or lead to losses of valuable timber resources due to disturbances such as bark beetle outbreaks, storms, droughts and other forest calamities. Increased demand for wood in heating networks could lead to a shortage of energy wood, resulting in non-residual wood being combusted. The cascade use principle must be enforced across a fragmented value chain to ensure wood reaches end-of-life use before being redirected to energy recovery.

BECCS: Chemical additives (such as amines) used in capture processes and the risk of GHG loss to the atmosphere (methane slip) during capture operations. High energy requirements for CO_2 separation can lead to gaps in the supply of thermal and electrical energy to the grid. The capture equipment may require significant adaptation of existing plant infrastructure.

DACCS: Land use, water consumption, and the potential release of captured chemicals into the environment are the main external costs. These are location-specific and require case-specific assessment beyond generic LCA methods.

CO_2 transport and storage infrastructure: Pipeline leaks and contamination of groundwater represent the main transport risks. For geological storage: leakages in the reservoir or during injection, groundwater contamination, and seismic risk from CO_2 injection into reservoirs must be assessed and covered by appropriate monitoring regimes. A rebound effect risk exists where higher consumption of fossil energy results from reduced production costs if CO_2 is injected into oil reservoirs for enhanced recovery.

Insurance and risk-sharing mechanisms for non-permanence and long-term liability are not yet adequately developed in Switzerland. For geological storage in particular, the liability horizon extends beyond any conventional investment cycle – potentially to centuries – making pure private financing untenable and requiring explicit state backstop mechanisms to be established in the CCS framework act. The concept of liability transferring to a national fund or public authority after a defined period of demonstrated integrity should be evaluated as part of the framework design.

5.6 Q6: Which CO_2 transport options are supported by the public and how might policies affect distributive impacts?

5.6.1 Public acceptance of CO_2 transport options

Overall public acceptance for CO_2 transport options is high. Across all six transport scenarios tested in the representative survey (3,058 respondents from German-speaking Switzerland, November 2025), approximately half of respondents actively support the assigned transport option, 38% are neutral, and only approximately 12% are opposed – meaning roughly 90% are neutral or supportive. This is a substantially more favourable starting point than is typically assumed in infrastructure planning and should inform both routing strategy and public communication.

Repurposed existing pipelines receive the highest acceptance of all options. Reusing existing pipeline infrastructure is significantly more accepted than constructing new underground pipelines – a finding with direct implications for routing strategy and for the role of the gas and oil industry as a partner. New underground pipelines also receive high support but score significantly lower than repurposed infrastructure. Rail transport is slightly preferred over electric trucks, though not to a statistically significant degree. Adding safety information about hazardous goods regulations had no effect on support for rail or truck options. However, informing respondents that CO_2 transport already takes place in Switzerland for industrial purposes significantly boosts support across all transport options – a relevant finding for public communication strategy.

Those with negative attitudes tend to be older, less concerned about climate change, possess less knowledge of climate-friendly behaviour, feel less personally responsible, and have lower trust in government and climate researchers. Gender, income, canton, and household size were not statistically significant predictors of opposition. This socio-demographic profile suggests that general climate communication and trust-building measures are more relevant than spatially targeted or income-based interventions for maintaining or expanding public support.

5.6.2 Acceptance of storage methods

Geological CO_2 injection is the least accepted storage method by a wide margin: 59.9% of respondents reported feeling uncomfortable with it, compared to approximately 26% for solid biochar stored in subsurface pits, a difference of 34 percentage points for interventions of broadly comparable permanence and depth. This acceptance gap is a governance liability that has not yet been adequately addressed in public communication strategies. Onshore geological storage will face greater public resistance than offshore options, and domestic siting decisions will require early and structured stakeholder involvement at cantonal and municipal levels.

However, the general disposition toward domestic geological storage if conducted safely is positive: 73.4% of respondents support it in principle. This suggests that the challenge is one of communication and trust-building rather than fundamental opposition, a distinction that matters considerably for how public engagement strategies are designed. Early and transparent public involvement, combined with a demonstrated preference for existing infrastructure corridors where feasible, is the communication approach most likely to preserve this broadly neutral to positive baseline.

5.6.3 Distributive impacts of CDR policies

An analysis of the garbage bag tax (pay-as-you-throw fee levied through charged bags) finds that this instrument has a regressive distributional effect compared to achieving equivalent waste reduction objectives through direct regulation. Lower-income households bear a disproportionately higher burden relative to income when waste reduction targets are pursued through a price instrument rather than a regulatory standard. This finding is directly relevant to the design of financing mechanisms for CCS at incineration plants: making consumers pay for CCS through higher waste disposal fees would similarly be regressive, since low-income households use a larger fraction of their expenditure budget on waste disposal and would profit less from any income tax reductions afforded by associated revenues.

A related question concerns the potential for perverse behavioural responses: whether increases in waste fees (implemented through higher garbage bag charges) would lead to increased illegal dumping of waste in the environment. This trade-off between price-based incentives and compliance behaviour is a key consideration for the design of municipal waste policy and for the broader question of how to finance carbon capture at waste incineration plants without generating unintended negative externalities. Instrument design must therefore weigh cost efficiency against distributional equity and behavioural risks, and command-and-control approaches may be preferable to price instruments in contexts where illegal dumping is a realistic response.

6 Policy recommendations

Achieving net zero in Switzerland by 2050 – including aviation emissions – requires active international cooperation on CO_2 transport infrastructure, storage capacity, and sequestration know-how. Switzerland should continue to engage in bilateral and multilateral frameworks to secure access to European CO_2 storage sites, while simultaneously supporting domestic storage solutions, which are publicly preferred and reduce strategic dependence on a single partner country.

Establishing clear national and internationally compatible investment frameworks for carbon management at the earliest opportunity is the single most important cost-reduction lever available to policymakers. Regulatory uncertainty raises the risk premium on private investment, delays deployment, and increases long-run abatement costs. Early commitment to stable policy conditions is therefore not merely administratively desirable but economically necessary to support innovation and deployment.

Since foreign offsets shift Switzerland's terms of trade in ways that increase welfare costs beyond their market price, **preference should be given to domestic emissions reductions and removals.**

Certain no-regret options – including timber construction (TCCS), biochar, and CO_2 capture at biogas plants – are technically feasible today and should be prioritised immediately. They deliver abatement benefits under a wide range of future scenarios, the first two do not depend on novel infrastructure or international market conditions, and face constraints that are regulatory rather than technological. Removing those regulatory constraints is an immediate policy priority.

Under normal geopolitical conditions, the scarcity of affordable renewable energy and storage capacity means that **large-scale domestic DAC and CCU should not be prioritised at this stage** relative to other abatement options. Investment decisions in this area should be conditioned on a realistic assessment of Switzerland's integration into international energy and carbon markets and reserved for scenarios of supply isolation or where DAC is co-located with suitable storage geology.

6.1 Timber in construction (TCCS)

A certificate system may be one effective tool for incentivising TCCS as it provides financial incentives through carbon market revenues, but it is only one instrument among many. The regulator should weigh its advantages against alternatives such as mandatory building standards like stringent implementation of SIA 390/1, public procurement requirements, and direct subsidies before deciding on the optimal policy mix. Public procurement is the most immediately available lever: the Forest Act already obliges the federal government to promote Swiss timber in federal buildings, and this obligation should be actively enforced and extended to cantonal and municipal procurement. The MuKEn 2025 could also increase demand for timber construction, but this may take time: the MuKEn 2014 have still not been implemented in all cantons (Solothurn is the exception), and the flexibility the MuKEn 2025 allow may lead to SIA 390/1 limit values that do not effectively require the use of wood. Designing climate policy beyond 2030 requires attention not only to the composition of the policy mix but also to its sequencing, i.e. the order and timing in which individual instruments are introduced.

Flanking measures along the entire forest–wood value chain are needed to ensure that increased demand for timber construction translates into additional use of Swiss timber rather than primarily imported wood, as this provides the opportunity to adopt Swiss forests to climate change. This would include incentives for Climate Smart Forestry, support for integrated forest–wood value chains, and targeted programmes to establish and maintain climate-resilient high-value timber species that secure future timber availability for long-lived applications. Strengthening the resilience of forests against disturbances such as drought, storms and bark beetle outbreaks should be recognised as a prerequisite for the long-term success of TCCS. Concrete measures include training programmes and a skills offensive for the timber sector from forest management through sawmills to manufacturing; information campaigns for architects, real estate developers, and institutional investors; and the establishment of a building materials register or building resource passport to track biogenic carbon in the built environment. The latter would enable the voluntary carbon market to coexist with compliance-based schemes by closing the current information gap on whether wood has already been credited elsewhere, thereby reducing the risk of double counting.

Lengthy discussions within the DeCIRRA project, as well as recently published literature on approaches to addressing non-permanence in nature-based CDR (Venmans et a. 2025; He et al. 2026; Gupton et al. 2026; Geden et al. 2026), demonstrate that finding workable solutions to incentivise TCCS in a carbon market approach remains deeply challenging. Using non-durable TCCS certificates to offset short-lived methane emissions appears to be the most straightforward option. Balancing practicable standards

against robust environmental integrity is the central challenge. Experience with the existing Swiss TCCS approach suggests that it is questionable whether the criticisms raised can be resolved through incremental methodological adjustments or are systemic in nature, which raises the broader question of whether the HWP/inventory-based approach offers meaningful advantages over project-level alternatives or if regulation would be the best choice. As things currently stand, crediting the carbon storage to sawmills and similar actors has drawn criticism both from other key stakeholders such as cantons and cities and from the voluntary carbon market, as they fear double counting. It therefore remains to be clarified who would be better placed to drive TCCS investments: the investors in the buildings or the timber industry. With the revision of the Swiss climate policy framework in 2030 providing a timely opportunity for more fundamental reform, it is advisable to conduct a structured comparison of available options to incentivise TCCS and be open to a system that is more compatible with international approaches.

To sum up, if the regulator introduces removal certificates as an incentive mechanism, the following conditions should be met:

- Their use should be restricted to offsetting emissions from genuinely hard-to-abate sectors – agriculture, waste incineration, and cement – rather than from the transport sector, which is the current arrangement and does not meet this criterion.
- The 30-year permanence requirement in the current Swiss CO_2 Act is incompatible with international standards and must be revised to align with Paris Agreement Article 6 rules and the EU CRCF.
- End-of-life treatment must be embedded in certificate design in a way that reflects the temporary nature of biogenic carbon storage and preserves environmental integrity. One option is to restrict the use of timber storage certificates to offsetting short-lived GHG emissions such as methane, which better matches the time profile of timber storage to the emissions being offset.
- To allow voluntary and compliance carbon markets to coexist without double-counting, the FOEN registry should be made more transparent, for instance through publicly visible project identification codes that display issuance and retirement status.

6.2 Biochar and hydrochar

Current legislation contains gaps and inconsistencies that impede the production, storage, certification, and trading of biochar and hydrochar, and particularly hinder the development of pilot projects and the scaling of hydrochar-based carbon removal. A coherent regulatory framework should be established that explicitly addresses these activities, removes conflicting provisions, and provides legal clarity for operators and investors. In developing this framework, Switzerland should align with EU regulations and draw on the experience of countries with more advanced biochar and hydrochar governance, to ensure compatibility with emerging international markets and standards. Until a comprehensive regulatory framework is established, Switzerland should examine the use of Article 48a of the Environmental Protection Act as a basis for enabling controlled pilot projects for the underground storage of hydrochar under clearly defined monitoring, reporting and environmental safeguards.

Specific barriers to address include the classification of hydrochar as waste under the Waste Ordinance, which prevents it from being marketed as a soil amendment or construction material, and the restrictive application limits for biochar in agriculture, which prevent the market from scaling. More research is needed to solve the outstanding scientific questions on soil impacts, carbon permanence, and PAH risks that underpin more permissive regulation, given that long-term studies for Swiss conditions are currently lacking.

On the demand side, methodologies under Art. 6 need to be approved so that more international demand for biochar and hydrochar projects emerges. Not a single biochar project has yet been accredited under the Swiss compliance scheme.

6.3 Carbon capture and storage at waste incineration plants (BECCS)

Waste incineration plants are one of Switzerland's most significant hard-to-abate emission sources, and CCS at these plants is a necessary component of any credible net-zero pathway. A central policy question is how to finance this investment. Three options merit consideration.

The first would be to leave it to the owners – mainly cantons and municipalities – to find a solution, which may increase the household disposal fees. The second is inclusion in the existing emissions trading scheme, which would place a carbon price directly on incineration operators. Given that in its revision proposal the EU Commission is planning to integrate waste incineration plants into the EU ETS from

2031 onward, the likelihood of this second option has increased. Further assessment needs to be done if the price would be high enough to encourage CCS investment when taking the removal certificates into account. The third, and most structurally novel, would extend the logic of Switzerland's advance recycling contribution (vorgezogener Recyclingbeitrag, vRB) to plastic packaging and other fossil-based waste. Under the vRB, manufacturers and importers of PET; electrical and electronic devices already pay a small fee at the point of sale that finances collection and proper treatment at end of life. Applying the same upstream obligation to producers and importers of plastic packaging would embed the carbon cost of incineration at the point of market entry, allowing it to propagate through the value chain to consumer prices. This makes the climate cost of non-energetic oil use visible without requiring increases to household waste disposal fees – avoiding both the regressive distributional effects of higher charges and the risk of incentivising illegal dumping.

6.4 CO_2 transport and storage

All existing pipeline infrastructure must be systematically assessed for CO_2 repurposing before new pipeline construction is approved, given that repurposed pipelines receive significantly higher public acceptance than new underground construction. Where repurposing is technically or economically infeasible, the reasons must be disclosed publicly in accessible terms. Transparency about what has been evaluated and why options were ruled out reduces perceptions of opaque decision-making and helps maintain the broadly positive public baseline.

Public communication about CO_2 transport is a policy instrument in its own right, not merely a flanking measure. Survey evidence shows that informing the public that CO_2 transport already takes place in Switzerland for industrial purposes – for example, transport to chemical plants or the beverage industry via road and rail – significantly increases support across all transport options. This information should be proactively communicated by authorities and operators rather than treated as a technical detail. Communication requirements should be mandatory, specifying minimum disclosure obligations covering infrastructure assessments, repurposing decisions, safety records, and planned expansions, subject to independent oversight.

Early and structured public involvement at cantonal and municipal levels is particularly important for geological storage siting, where acceptance is significantly lower than for transport options. The survey shows 73.4% of respondents support domestic geological storage in principle if conducted safely; the challenge is therefore one of trust-building rather than fundamental opposition and should be approached accordingly.

Switzerland should negotiate and conclude long-term CO_2 offtake agreements with multiple international storage partners – not only Norway but also Denmark, the Netherlands, and potentially Italy – to avoid strategic dependence on a single partner country. The bilateral agreement with Norway is a first step and should be followed by equivalent agreements as European storage infrastructure matures. Germany and France should be engaged as key transit countries, with PCI project status pursued for the relevant cross-border pipeline segments.

6.5 Policy instruments

Carbon management approaches typically do not produce a marketable product, making their business models structurally dependent on credible, long-term regulatory frameworks. Policy instruments must therefore provide sufficient certainty over planning horizons that match the capital intensity of CMA projects. Frequent regulatory revisions, unclear liability rules, or uncertain demand signals are themselves barriers to investment and should be avoided.

Instrument design must account for market dynamics: under open international competition, markets will tend to select and finance the cheapest available options. In an internationally open carbon removal market, low-cost approaches such as ocean alkalinity enhancement could set the price floor for removals, potentially crowding out more expensive but domestically strategic options. Policymakers should therefore consider whether a purely market-driven instrument achieves the desired portfolio of removal approaches, or whether complementary mechanisms – such as technology-specific support, minimum quality standards, or domestic content requirements – are needed to ensure a resilient and diversified carbon management sector. Future research could assess the effectiveness of specific policy instrument combinations and sequencing for different CMA and business model types.

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8 Appendix

Appendix 1: Events, Workshops & Meetings organised by DeCIRRA
(This table lists the most important events, but there were many more small and bilateral meetings)

Table A1: DeCIRRA SP3 events, organised and visited workshops, and meetings.

When	Title	Description	Participants
9.3.2022	Kick-off SP3 (online)	Introduction of team and project	SP3 research partners
16.3.2022	WS actor network (online)	Preparation, visualisation and analysis of an actor network, input from specialists	SP3 research partners
18.5.2022	Kick-off DeCIRRA (in person)	Introduction of team, project and work processes	DeCIRRA partners
31.5.2022	Biochar KLIK	Exchange about the opportunities of biochar as NET	KLIK, Betz
23.6.2022	SPIN Day with contribution by DeCIRRA	CO_2 transportation, pipeline…	Betz, Marchand, Biollaz & many others that are not part of DeCIRRA
5.10.2022	WS biochar	DeCIRRA and biochar, merit order data, actors	Open for all those interested in biochar
14.10.2022	Conference: SFOE on NET	CO_2 removal and storage: Necessity and pathways to implementation	Various experts from science, business and politics
2.11.2022	WS CO_2 pipeline	Who, how, where CO_2 pipeline Switzerland	DeCIRRA SP3 and further experts
8.11.2022	WS wood construction as NET	Wood construction status update	Timberfinance, core team
7.12.2022	WS CO_2 pipeline (online)	Continuation and clarification of WS from 2.11.	DeCIRRA SP3 and further experts
27.1.2023	Conference: Disentis CO_2 pipeline	Various inputs and WS at the Energy research conference in Disentis	DeCIRRA and others
31.1.2023	Conference: DemoUp Carma	Networking with the DemoUp Carma project, with which there are many links	Betz and others
13.3.2023	Expert discussion CO_2 pipeline	Exchange between cement industry and project	
20.3.2023	WS biochar (online)	Regulation, standards, framework conditions, co-benefits of biochar	DeCIRRA and others
28.4.2023	Event NET Suisse		
10.5.2023	WS milestone policies and data	Overview of policies, support and pseudo merit order for NET	SP3 research partners and guests
	NET networking event	Exchange with other large projects on NET, including DemoUp Carma, CDR Speed2zero, ZCMA…	
End of July 2023	Report milestone 1	Coordination and finalisation of the milestone report	
23.10.2023	Meeting on timber construction accounting	Exchange on standards for timber construction, e.g., Verra	
16.11.2023	Scenario workshop with ETHZ	Preparation and exchange over the possible scenarios and methods	ETH, SP3 research partners other experts
Winter 2023	Inventory accounting workshops (online)	Several workshops on preparation of inventory and accounting methods	
Jan 2024	SP3 update	Meeting to bring together the latest findings and plan the coming year	SP3 research partners and guests

When	Title	Description	Participants
6.3.2024	Modelling Workshop	Bündelung und Synchronisierung von nationalen Modellierungsaktivitäten	DeCIRRA & guests
13.3.2024	DeCIRRA Site Visit	Innosuisse DeCIRRA Site Visit	DeCIRRA members
23.4.2024	Business Model Workshop	collect and share your insights into possible NET business models	SP3 research partners and guests
31.5.2024	Szenarien workshop	Planning of the CMA Szenarios	SP3 research partners
27.6.2024	HTC Szenarien	How should HTC be introduced in the model	SP3 research partners and guests
28.6.2024	SP3 Update	Reflect on results and plan the next steps	SP3 research partners
11.7.2024	Planning Scenario Report	This and many following meetings for the scenario report.	SP3 research partners
13.12.2024	TCCS Workshop	Bringing together stakeholders & current information on TCCS	SP3 research partners and guests
13.12.2024	Hydrochar Technology Workshop	Bringing together stakeholders & current information on Hydrochar	SP3 research partners and guests
17.12.2024	SP3 Update Meeting	SP3 Meeting to reflect the last year and plan the new year	SP3 research partners and guests
28.1.2025	Yearly DeCIRRA conference in Bern	Meeting to reflect the last year and plan the new year	SP3 research partners and guests
7.2.2025	White Paper Workshop	Planning and finalisation of the White Paper	SP3 research partners
24.4.2025	Innosuisse on Site visit	Meeting with Innosuisse	Whole DeCIRRA Team
24.6.2025	Workshop BSCR	Bio-based Solid Carbon Removal formation of working group	SP3 research partners and guests
8.7.2025	Workshop BSCR	Bio-based Solid Carbon Removal	SP3 research partners and guests
24.9.2025	Online: Expert Workshop on BSCR	Bio-based Solid Carbon Removals as an Opportunity for Cities and Regions to reach Net Zero by 2040	SP3 research partners and guests
1.12.2025	Vor Ort: TCCS Anrechenbarkeit	Temporäre Kohlenstoffspeicherung im Lifecycle von Wald und Holznutzung – Welche methodischen Lösungen zur Anrechenbarkeit gibt es?	SP3 research partners and guests
15.12.2025	Online: TCCS Anrechenbarkeit	Abstimmung Handlungsempfehlungen Kohlenstoffspeicherung im Holzbau	SP3 research partners and guests
16.12.2026	SP3 Yearly Update	End of the year update and summary of project results	SP3 research partners and guests
20.1.2026	Abschlusskonferenz in Bern	In place final conference to present the project results	Whole DeCIRRA consortium and guests
17.2.2026	Biomasse Verwendung	Absprache mit CEMsuisse und anderen Akteuren zur Biomasse Nutzung	SP3 research partners
15.4.2026	Handlungsempfehlung TCCS	Abstimmung Handlungsempfehlungen Kohlenstoffspeicherung im Holzbau	SP3 research partners and guests
7.5.2025	CMA Business Model Workshop	Synthesis Workshop to get feedback and reflect on the results of the Business Model research	SP3 research partners and guests
4.6.2026	TF BSCR Meeting	Taskforce Biochar, Hydrochar Working Meeting	SP3 research partners and guests
1.7.2026	SP3 Closing Meeting	Finalisation and Coordination of the final report	SP3 research partners

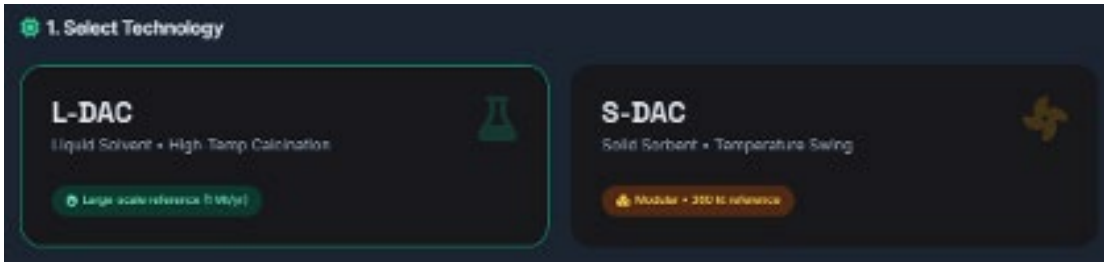
Appendix 2: DAC calculator

The DAC TEA Calculator is a lightweight, client-side web application that allows users to instantly compare the economics and performance of two major DAC technologies: L-DAC and S-DAC. Users select a technology, adjust general project parameters (plant scale, energy prices, financials, etc.) and technology-specific inputs, and receive immediate results including:

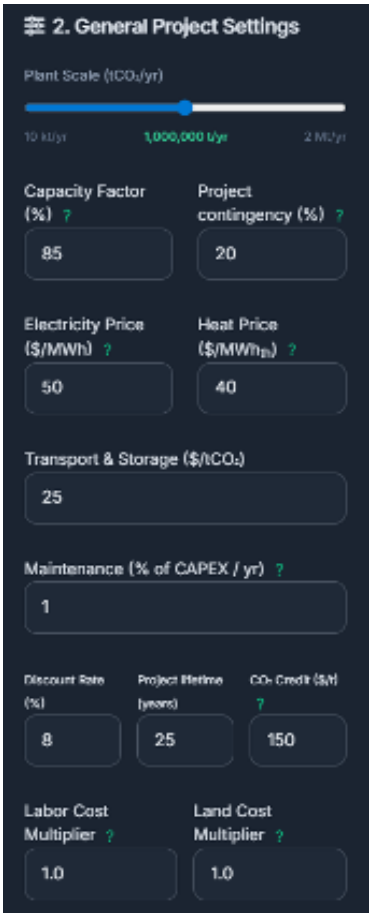
- Levelized Cost of Capture (LCOC)
- CAPEX / OPEX breakdown
- NPV, IRR, payback period
- Energy & resource metrics
- Sensitivity analysis (tornado chart)

Tool Overview & Features

1. Technology selector
   - Toggle between L-DAC (liquid solvent, high-temperature regeneration) and S-DAC (solid sorbent, temperature/vacuum swing).



2. Input panels
   - General Project Settings (common to both technologies)
   - Technology-Specific Parameters (auto-updates when switching tech)





3. Real-time results
    - Economic dashboard with LCOC, total CAPEX, annual OPEX
    - Cost waterfall chart & OPEX pie chart
    - NPV, IRR, payback, breakeven carbon price
    - Future LCOC projections (2030/2040/2050) with learning curve
    - Technical metrics (energy use, water, land, material intensity, net removal)
    - Interactive sensitivity tornado chart



Methodology

The tool implements a simplified Levelized Cost of Capture (LCOC) framework, consistent with published DAC techno-economic assessments. Core Approach:

- Scale plant capacity using a power-law cost curve.
- Calculate total CAPEX with contingency.
- Annualize capital using the Capital Recovery Factor (CRF).
- Compute variable and fixed OPEX components.
- Subtract CO_2 credit revenue.
- Derive LCOC as net annual cost per tonne captured.
- Perform financial metrics (NPV, IRR approximation, payback).
- Apply a constant learning rate for future projections.
- Calculate technical performance metrics using technology-specific coefficients.

Key Assumptions:

- Constant annual capture (no degradation over lifetime).
- Single reference scale = 100 kt CO_2/year.
- Learning rate = 3% per year (≈15% every 5 years).
- Net removal efficiency = 96% (accounts for process emissions).
- No location-specific climate adjustments (can be added in future versions).

Key Formulas

- Annual CO_2 Captured

$$Annual\ captured\ =\ Plant\ scale\ \times \frac{Capacity\ factor}{100}$$

- Scaled Specific CAPEX

$$Specific\ CAPEX\ =\ Base\ specific\ CAPEX\ \times \left(\frac{Scale}{100'000}\right)^{Scaling\ exponent\ -\ 1}$$

- Total CAPEX

$$Total\ CAPEX\ =\ Specific\ CAPEX\ \times Scale\ \times \left(1+\frac{Contingency}{100}\right)$$

- Capital Recovery Factor (CRF)

$$CRF\ =\ \frac{r\ \times\ (1+r)^n}{(1+r)^n-1}$$

where:

r = discount rate,
n = lifetime (years)

- Annualized CAPEX

$$Annualized\ CAPEX\ =\ Total\ CAPEX\ \times\ CRF$$

- OPEX Components (per year)
  - Electricity cost:
    $$Electricity\ cost\ =\ (Elec\ req \times Annual\ captured\ /\ 1000) \times Elec\ price$$
  - Heat cost:
    $$Heat\ cost\ =\ Heat\ req\ \times\ Annual\ captured\ \times\ Heat\ price$$
  - Material cost:
    $$Material\ cost\ =\ Material\ rate\ \times\ Material\ cost\ \times\ Annual\ captured$$
  - Maintenance:
    $$Maintenance\ =\ Maintenance\ rate\%\ of\ Total\ CAPEX$$
  - Labor:
    $$Labor\ =\ 480'000\ \times\ (Scale/100'000)^{0.35}\ \times\ Labor\ multiplier$$

- **Levelized Cost of Capture (LCOC)**

$$LCOC\ =\ \frac{Annualized\ CAPEX\ +\ Total\ OPEX\ -\ Revenue}{Annual\ captured}$$

- Revenue

$$Revenue\ =\ Annual\ captured\ \times\ CO_2\ credit\ price$$

- **Net Present Value (NPV)**

$$NPV\ =\ -Total\ CAPEX\ +\ (Revenue\ -\ Total\ OPEX)\ \times\ PV\ factor$$

$$PV\ factor\ =\ \frac{1-(1+r)^{-n}}{r}$$

- **Future LCOC Projections**

$$LCOC_t\ =\ LCOC_{base}\ \times\ (1-0.03)^t$$

(assuming 3% annual learning rate)

Appendix 3: Policy measures proposed by Swiss CMA stakeholders

Table A2: Policy measures proposed by stakeholders to support the development and testing of CDR technologies until 2030 (adapted from Dittli 2023).

Category	Description of policy instruments until 2030	N
Legal regulations and framework conditions	Klare/stabile Rahmenbedingungen / Regulierungen (ohne weitere Erklärung), um Sicherheit für Privatinvestoren zu bringen	11
	Klare Zielsetzungen für den Umgang mit CO_2-Entnahme und -Reduktion. Z.B.: Emissionsgrenzwerte (Stand der Technik / beste verfügbare Technologie) definieren, sanktionierbare Zielvorgaben, etc.	8
	Erleichterte Rahmenbedingungen (z.B.: Genehmigungen für CDR Anlagen vereinfachen, regulatorische Hindernisse abbauen)	7
	Einführung des CO_2-Gesetzes / Verankerung im CO_2 Gesetz	4
	Entwicklung einer ganzheitlichen Strategie für CDR und CCU-Optionen, um zu vermeiden, dass einseitige Fokussierung aus CDR systemrelevante Möglichkeiten zur Energiespeicherung, Stromerzeugung (Biomasse) und Dekarbonisierung verhindert.	4
	Klare Richtlinien/Regulierung von CO_2-Entnahmeaktivitäten, sowohl im Inland als auch im Ausland. Das beinhaltet, z.B.: Standards, die festlegen welche Aktivitäten als CO_2 Entnahme gelten (z.B. Haltbarkeit der CO_2 Speicherung); Monitoring, Reporting and Verifikation um CO_2 Leakage zu vermeiden/ zu beobachten; Geldreseven, die bei CO_2 Leakage einspringen können um das Entwichene CO_2 wieder zu entnehmen; rechtliche Verantwortlichkeiten und langfristige Haftungsregeln).	4
	Richtlinien für die Beschaffung von Produkten / Public procurement (inkl. Benutzung von CDR Zertifikaten für Kompensation in der Administration)	3
	Regelung der Anrechnung von abgeschiedenem CO_2 für Unternehmen (z.B. Anerkennung in THG Bilanz und entsprechende Methodiken)	2
	Sektorale Verträge zwischen Behörden und Industrie	1
	Verschärfte Massnahmen und Kompensationspflichten für Sektoren, die ihre Emissionsziele nicht erreichen	1
	Nachrüstungspflicht für grosse Emittenten zur Vermeidung vor Kompensation	1
	Miteinbezug der Grenzkantone bei der Erarbeitung von Transportlösungen.	1
	Wissenschaftlich unabhängige Life-Cycle-Assessments mit der Abschätzung der Risiken.	1
Financial support and incentives	Bereitstellung von Fördergeldern für Forschung, Entwicklung und Demonstrationsprojekte	14
	Finanzierung von Anlagen/Projekten klären/sichern/angehen/unterstützen/vereinfachen (ohne weitere Erklärung wie)	12
	Ausbau von Förderprogrammen und Investitionsbeiträgen für NET-Anlagen	6
	Carbon Contracts for Difference, um Preislücke zu schließen	3
	Festgelegter, kontinuierlich ansteigender CO_2-Preis. Damit werden die Kosten für die Emittenten berechenbar und Investitionen können geplant werden. Wichtig ist, dass es keine Obergrenze gibt. Dann erkennt jeder, dass es umso teurer wird, je länger er wartet.	3
	Ausweitung des Schweizer Technologiefonds zu einem Schweizer Carbon Removal Fonds	1
	Schaffung von Anreizen für den Einsatz von CO_2-Entnahme-Technologien durch eine markante Erhöhung des Preises für Klik-Zertifikate	1

	Defizitgarantien für first movers	1
	Garantien setzen für die Grossinvestitionen insb. für gemeinsame Infrastruktur-Bedarfe, die sonst nicht getätigt werden.	1
	Vergünstigte Elektrizitätspreise für Verflüssigung von CO_2	1
	Anschubfinanzierung für CO_2 Logistikkette (z.B. Bahnverladeanlagen)	1
	Förderung der Industrien mit sehr hohem Potential (beste Skaleneffekten, z.Bsp. Zement, KVA's) zu CCS / CCU / NET bevorzugen. Direct Air Capture oder CO_2 in Beton zu speichern ist deutlich ineffizienter.	1
	CCS soll auch durch den Verursacher bezahlt werden.	1
	Zurückhaltende Subventionierung, nur in Zusammenhang mit Startfinanzierung/Forschung/Pilotprojekten. Mittel- und langfristig müssen sich Innovationen selbst tragen (Subventionen machen abhängig) —> darum: wirtschaftliche Investitionen nicht subventionieren (falsche Anreize)	1
	Weitere Anreize (Steuerliche Anreize, Unterstützende Lenkungsmassnahmen, Unterstützung von freiwilligen Aktivitäten im Bereich CDR)	3
Creation of infrastructure and networks	Ausbau von CO_2-Transportinfrastrukturen	3
	Schaffung einer Organisation aus Behörden und Privatunternehmen zur Koordination und Umsetzung von CO_2-Entnahme-Massnahmen	3
	Einrichtung von CCS/CCU/CDR-Hubs und Clustern	1
	Massiver Ausbau an erneuerbaren Energien und Projekte, welche die Infrastruktur für deren Verteilung garantieren.	1
	Erarbeitung von Business Modellen für alle verschiedenen Emittentengruppen	1
International cooperation and agreements	Abschluss von internationalen Verträgen zur Regelung des Transports und der Speicherung von abgefangenem CO_2	4
	Klärung und Beseitigung regulatorischer Hemmnisse für den internationalen Transport und Handel mit CO_2-Entnahme (Zoll, Deklaration Abfall/Chemical)	2
	Artikel 6-Pilotprojekte Schweizer CDR Technologieanbieter im Ausland	1
Communication and awareness creation	Informationskampagnen, um die Bedeutung von CO_2-Entnahme-Massnahmen der breiten Bevölkerung näherzubringen	2
	Förderung von Fachverbänden und Wissensplattformen zur Schaffung von Austausch und Zusammenarbeit	2
	Transparenz über die Deklaration von CO_2 bei Produkten. Mit klaren Berechnungs- und Deklarationsmethoden (z.B. CO_2-freie vs CO_2-reduzierte vs CO_2-emitierende Produkte).	1
	Lichtturmprojekte und Startups im öffentlichen Diskurs präsentieren, um Investoren zu finden.	1
Specific on CO_2 markets	Robuster Markt für den Handel mit NET-Zertifikaten aufbauen (inkl, z.B., Koordination mit EU, langfristige Abnahme von NET-Zertifikaten, verpflichtende Abnahme von NET-Zertifikaten, Anrechenbarkeit im EHS).	5
	Preiskorridore	1
	Klare Richtlinien für CDR-Zertifikate	1

	Im Rahmen des ETS ist CBAM nötig.	1
Specific on biochar	Grundbucheintrag beim Einsatz von Pflanzenkohle in der Landwirtschaft wieder aufheben	2
	Herunterfahren von Subventionen und Klimaschutzgutschriften für die komplette Verbrennung von Biomasse (und damit Vernichtung der möglichen Senkenleistung)	1
	Klassifizierung von Biokohle aus unterschiedlichen Substraten und deren Zulassung für die Einbringung in den Boden (Zertifizierung).	1
	Wissenschaftlicher, fundierter Umgang mit Pflanzenkohle in der Gesetzgebung und den Vorschriften zur Anwendung von PK in der Landwirtschaft (Ängste der Bodenschützer abbauen, Verständnis über die Wirkung und Eigenschaften der Pflanzenkohle bei zuständigen Stellen fördern)	1
	Marktmechanismen fördern indem das CO_2 in allen Prozessen eingepreist wird, insbesondere in der Verwertung von Biomasse.	1
Specific on TCCS	Förderung / Abgeltung für Bauherren, welche mit Holz bauen	2
	Grenzwerte Finanzmarktregulierung für grüne Immobilienportfolios auf Grundlage Ökobilanzierung (Alle Indikatoren aus der KBOB Liste Ökobilanzdaten im Baubereich) von Gebäude Lebenszyklusphasen Nutzung, Herstellung und Entsorgung.	1
	Der Bund verlangt in einem Gesetz den Nachweis der Umweltauswirkungen bei allen Baueingaben auf Grundlage KBOB Ökobilanzdaten im Baubereich.	1
	Der Bund unterstützt die Entwicklung der digitalen Baueingabe auf Basis IFC - Austauschformat.	1
	Anpassung von Normen und Gebäudelabels	1
Specfiic for waste incineration plants	Gebühr/Steuer für Müll, die CCS bei KVAs finanziert	1
	Fokus auf Umrüstung der KVA mit carbon-capture-System	1
	Einbinden in das / Finanzierung über das Abfallgesetz oder andere existierende Gesetze.	1
	Stofflich/Thermische Abfallverwertung (Zementwerke) müssen vor der nur Thermischen Abfallverwertung stehen.	1
Specific for the agricultural sector	Maßnahmebezogene Förderung von landwirtschaftlichen Massnahmen, v.a. Agroforst	1

Table A3: Policy measures proposed by stakeholders to support the broad deployment of CDR technologies until 2050 (adapted from Dittli 2023).

Category	Description of policy instruments until 2050	N
Planning and organisation	Schaffung klarer/ausreichender Regulatoren / Rahmenbedingungen	5
	Unterstützung/Akzeptanz der Bevölkerung erreichen (u.a. durch Informationskampagnen)	5
	Kontinuierliche Arbeit und Zusammenarbeit zwischen Behörden und Privatunternehmen	3
	Offenheit der Behörden, Mut, Neues auszuprobieren, Bereitschaft, Fehler zu machen, Entscheidungsfreudigkeit	2
	Korrekte Abbildung der Synergien zwischen CDR, CCU/PtG (inkl. Produktion von grünem H_2) in den Regularien/Gesetzen/Marktregeln.	2
	Betrachtung der gesamten Nutzungskaskade	1
	Aufrechterhaltung des Drucks seitens NGOs, Politik und Gesellschaft	1
	Plan, wie CCUS mit anderen Massnahmen (z.B. Suffizienz) vereinbar ist.	1
	Berücksichtigung von CDR in nationalen Treibhausgasinventaren	1
	Die Politik muss langfristige Rahmenbedingungen setzen und die Umsetzung der Massnahmen der Wirtschaft überlassen. Sie soll lediglich moderat mit Förderung und Lenkung eingreifen.	1
	Wertewandel von einseitiger Geldorientierung (kurzfristig maximaler Gewinn für Wenige mit grossem Ressourcenverschleiss) zu umfassender nachhaltiger langfristiger und integraler Nutzenorientierung für Alle (mit weniger Ressourcen mehr Nutzen erzeugen).	1
	Raumplanerische Massnahmen begleitend von aufklärenden, sensibilisierenden Massnahmen, damit das Potenzial von CDR-Methoden maximiert wird.	1
	Vereinfachten Zugriff zu Kapitalgeber, Fördergelder & Investoren	1
	Zuerst müssen die Rahmenbedingungen erfüllt sein. Subventionen sind heute nutzlos, da die Grundlagen der Gesetzgebung vor allem bei der Entsorgung (USG, VVEA) nicht gegeben sind.	1
	Klare Definition von CDR. Einbettung von CDR in CH Klimapolitik. Vorbereitung hin zu einem vollumfänglichen Politikinstrumentarium für CDR mit dem Kern einer Art öffentlicher CO_2-Entsorgungswirtschaft (Vergleich mit heutiger Kerrichtabfuhr).	1
Regulatory measures	Einführung von verbindlichen CDR-Zielen/Zielpfaden, mit Sanktionen, eventuell sektoriell, über 2030 hinaus	10
	Einführung von Emissionsausgleichssystemen (od. Rücknahmeverpflichtungen), bei denen (ein Teil der) Restemissionen der Unternehmen durch technische CDR-Zertifikate kompensiert wird	5
	Einführung von verbindlichen Emissionsreduktions-Zielen/Zielpfaden (bis zum Netto-Null Ziel)	5
	Einführung der öffentlichen Beschaffung von qualitativ hochwertigem CDR, finanziert durch neue Einnahmequellen	1
	Einführung von Verboten	1
	Weitere Lesung des CO_2-Gesetzes mit sich verschärfenden Massnahmen	1

Category	Description of policy instruments until 2050	N
	Konsequente Anwendung von Ökobilanz-Nachweisen im Bausektor, Industriesektor und Finanzsektor.	1
	Weg von der Verbrennung.	1
	Lachgasemissionen sanktionieren oder vermiedene Emissionen belohnen.	1
	Gesetzliche Regelungen, die den Einsatz von CCS in grossen Punktquellen (Zement, Stahl, sonst. Industrie) wirtschaftlich möglich macht: z.B. degressive CO_2-Grenzwerte für Baumaterialien inkl. Grenzschutz für CH-Produzenten.	1
Financial support and incentives	Angemessener / kontinuierlich ansteigender CO_2 Preis	5
	Finanzfragen müssen schon geklärt sein.	3
	Verursacherprinzip bei der Finanzierung. (Keine Bundesgelder für die CO_2-Abscheidung und Speicherung. Die Kosten müssen durch die Emittenten getragen werden. Die Produkte wie z.B. Stahl oder Zement verteuern sich und werden weniger konkurrenzfähig gegenüber sinnvolleren Materialien wie z.B. Holz als Baustoff.)	3
	Einführung von Einnahmegarantien (oder garantierten Preisen für negative/vermiedene Emissionen), um Projekten Sicherheit zu geben	3
	Einführung von Steuergutschriften, die sich auf das investierte Kapital oder den Gewinn pro Tonne CO_2 beziehen	2
	Einführung von Subventionen zur Stimulierung des Sektors (wie SDE++ in den Niederlanden)	2
	Internalisierung externer Kosten	2
	Gesetzliche Verankerung einer Gebühr/Steuer für Müll, die die vollen Kosten für BiCRS in jeder Abfallverbrennungsanlage abdeckt	1
	Sinnvolle Finanzierung. Konkret bei unseren KVA: Nicht über eine zusätzliche Müllgebühr, sonst verdreifachen sich die Behandlungskosten. Dann findet der Müll neue Wege	1
	Verankerung ähnlicher Mechanismen für Biogas- und Biomasseanlagen sowie Zementwerke im Gesetz	1
	Entwicklung eines Förderprogramms mit umgekehrter Auktion (wie in Schweden)	1
	Einrichtung eines Instruments zur Finanzierung von Grossanlagen wie dem Europäischen Innovationsfonds oder dem dänischen CCS-Projektfonds	1
	Hohe und gesicherte Förderbeitrage zur direkten Unterstützung der Privatwirtschaft zur Kommerzialisierung von CDR-Technologien.	1
	Strukturelle Integration des CO_2 Preises in den Handel (das allerdings wird nur zumindest europaweit möglich sein, nicht nur in der CH)	1
International cooperation	Stärkung der internationalen Kooperation (insb. mit der EU) und Kapazitätsaufbau	5
	Prüfung des rechtlichen Rahmens (EU CCS Directive, London Convention/Protocol für den grenzüberschreitenden Transport)	1
	Da die Schweiz CO_2 nicht lagern kann, braucht es immer noch gute Transportunterstützungen	1
	Internationale Verträge zum Transport und zur Speicherung des abgefangenen CO_2.	1
	Vermeiden, dass CO_2 Emissionen importiert werden, d.h. Besteuerung CO_2 Emissionen auf	1

Category	Description of policy instruments until 2050	N
	importierte Produkte.	
	Verbindliche internationale Vereinbarungen zu Klimazielen	1
Infrastructure	Aufbau CO_2-Infrastruktur (Transport und/oder Speicherung).	10
	Die Energieversorgung (aus Erneuerbaren) muss sichergestellt sein.	3
	Zur Verfügungstellung von geeigneten Arealen für CO_2 Bahnverladeanlagen	1
Specific on CO_2 markets	Sukzessive Integration von CDR in compliance markets, inklusive das EU-Emissionshandelssystem (EU ETS) und das Schweizer ETS	3
	Kein Zertifikatehandel mehr, denn dies dient ja nur für die Kompensation und nicht für eine Reduktion der Emissionen	1
Specific on TCCS	MUKEN legen nicht nur Grenzwerte zu Umweltauswirkungen in der Lebenszyklusphase Nutzung, sondern auch in Herstellung und Entsorgung fest. (Primärenergie (inkl. allen Unterteilungen oder Treibhausgase)	1
	Der Bund führt in der Beschaffung als Vorbild die digitale Baueingabe auf Basis IFC - Austauschformat ein, inkl. Nachweis Umweltauswirkungen.	1
	Unterscheidung zwischen biogenem und fossilem CO2-Ausstoss ist aufzuheben. Dies dient nur dazu, CO_2-Emissionen "schönzurechnen", wie z.B. Herstellung von Zement mit alternativen Brennstoffen.	1
	Langfristig ist vollständig auf Stahlbeton am Bau zu verzichten.	1
Specific on forestry and agricultural sector	Die regenerative Landwirtschaft zusammen mit BECCS und Biochar (zusammen ein Massnahmen-Komplex) können alleine schon 2/3 der Aufgabe stemmen weltweit - in der Schweiz etwas weniger, weil wir unterproportional Nahrung selber erzeugen. Kein Dünger- und Futtermittelimport mehr bis dahin. Produktion aber trotzdem steigern - das geht. Wir können sogar Vollversorgung erreichen* Permakultur etc. Steingärten verbieten. Möglichst dreidimensionale, ganzjährige Begrünungen.	1
	Senkenleistung in der Land- und Forstwirtschaft erhöhen durch CO_2 Marktanreize aber auch durch Verbote gewisser schädlicher Praktiken wie die intensive Bewirtschaftung von organischen Böden.	1
	Positive Nebeneffekte von natürlichen CDR Massnahmen müssen zusätzlich zum CO_2 Speichernutzen monetarisiert werden (Emissionsreduktionen durch Pflanzenkohle im Feld, Biodiversitätsleistung von Agroforstsystemen etc.)	1
	Wald- Wild Problematik endlich lösen. Mit der Klimaerwärmung hat der Wald schon genug Probleme. Wenn sich die Wildproblematik nicht drastisch ändert, hat die Waldverjüngung keine Chance.	1
Further aspects	Finanzierung der Forschung und Entwicklung (z.B. aus der CO_2-Abgabe). Spezifisch genannte Forschungsbereiche: Utilization, Speicherlösungen, technische CDR Lösungen, Verwendung von Pflanzenkohle.	5
	Komplexe CDR-Technologien mit Mehrfach-Umweltnutzen wie Pflanzenkohle, Holznutzung, Biologische Methoden und Humusaufbau sind durch die Politik zu priorisieren. Diese Technologien sind komplexer, bringen aber gesamtheitlich neben dem CDR weit mehr für die Gesellschaft.	1
	Förderung der Industrien mit sehr hohem Potential (beste Skaleneffekten, z.Bsp. Zement, KVA's) zu CCS / CCU / NET bevorzugen. Direct Air Capture oder CO_2 in Beton zu speichern ist deutlich ineffizienter.	1

Category	Description of policy instruments until 2050	N
	Es sollten alle Möglichkeit der CO_2 Abscheidung, unabhängig von der Konzentration des CO_2, sofern es sich um eine indirekte Abscheidung handelt, gezielt unterstützen.	1
	Die konsequente Verknüpfung mit einer Kreislaufwirtschaft, mit besonderem Blick auf die Nutzung von Biochar im Kreislauf, statt Erdölprodukte	1
	Anpassung des Waldes an den Klimawandel	1

Table A4: Measures proposed by stakeholders for the development of transport and storage capacities (adapted from Dittli 2023).

Category	Measures for the transport or storage of CO_2	N
Legal and organisational preconditions	Klärung/Vereinfachung/Harmonisierung der rechtlichen Anforderungen für den internationalen/cross-border Transport von CO_2 (Klassifizierung als Abfall, Gefahrgut oder Produkt; EU CCS Directive; London Convention/Protocol for cross-border transport)	16
	Suche/Kartografieren von möglichen Speicherstätten in der Schweiz	9
	Unterzeichnung bilateraler Abkommen mit Ländern mit geologischem Speicherpotenzial (Norwegen, Dänemark, Niederlande); Besprechung konkreter Liefer- und Abnahmemengen	8
	Rechtsgrundlage für die Entwicklung einer Pipeline schaffen / Eine CO_2 Pipeline muss auf Bundesebene koordiniert werden. Verwaltung des Untergrunds ist offensichtlich Sache der Kantone.	4
	Rechtlicher Rahmen für Liability für den Fall von Leakage / Seepage (inkl. Versicherungsmodi + private-public partnerships um Risiken zu reduzieren)	2
	Start der Planung / Entwicklung eines Business Plans für die Pipeline (Arbeit könnte z.B. von der Regierung in Auftrag gegeben und von einer öffentlichen oder privaten Forschungseinrichtung durchgeführt werden).	2
	Planungstechnische Schritte zur inländischen Speicherung (Untergrund und Produkte) unternehmen (inkl. öffentlicher Debatte).	2
	Stimulierung der Bündelung von Mengen durch nationale oder regionale Planung und die Förderung von Clustern	1
	Entwicklung einer Kartierung der Emittenten von Punktquellen und potenziellen Clustern und Ermöglichung der Zusammenarbeit innerhalb solcher Cluster	1
	Erstellung eines nationalen Registers für Emittenten von Punktquellen, die am Transport von CO_2 interessiert sind	1
	CO_2 muss im Inland gespeichert werden. Export ist keine Option.	1
	Fokus auf internationale Kooperation statt inländischer Speicherung.	1
	Die Speicherung und der Transport von CO_2 ist immer noch ein linearer Prozess. Besser wäre ein Kreislauf wie beim Holz. Wenn die Zementindustrie die Speicherung, Transport und Lagerung selber bezahlen muss, wird sie langsam verschwinden und damit auch die Erfordernis zur Speicherung und zum Transport von CO_2.	1
	Die Speicherung zulassen	1
	EU-Rahmenabkommen mit entsprechenden Ergänzungen	1
	Es braucht einen klaren Rahmen und eine Strategie des Bundes, um ein geplantes Hochfahren der Transportlogistik - Tanks/Zug/Schiff - Pipeline - durch privatwirtschaftliche, resp. parastaatliche Akteure zu ermöglichen.	1

	Risiken und Konflikte müssen von einer unabhängigen Instanz analysiert werden.	1
	Speicherung: Das BWL und BAFU darf aus meiner Sicht offener werden im Bereich Einsatz von EBC-AgroBio Pflanzenkohle (hochwertige Pflanzenkohle) in landwirtschaftlichen Böden.	1
	Transport und Lagerung muss auditiert und zertifiziert werden. Dazu benötigt es ein Qualitätssicherungssystem und klare politische Vorgaben	1
	CO_2 Transport Vorschriften aufheben	1
	Die Infrastruktur muss allen Nutzern zu gleichen Konditionen bereitgestellt werden	1
Financial support and incentives	Bereitstellung öffentlicher Infrastruktursubventionen.	3
	Schlüsseltechnologie HTC für die biologische Speicherung fördern.	1
	Garantien setzen (Einnahmegarantien oder anderen Mechanismen zur Risikominderung) für die Grossinvestitionen insb. für gemeinsame Transport Infrastruktur-Bedarfe, die sonst nicht getätigt werden.	1
Research	Einleitung von Forschungsarbeiten zu neuen CO_2-Transportoptionen im Inland (z. B. Iso-Tanks auf der Schiene)	1
	Untersuchung der Durchführbarkeit von CO_2-Railtanks, die heute kurze CO_2-Haltezeiten haben und für lange Fahrten zu den Lagerstätten noch ungeeignet sind	1
	Untersuchung weiterer Transportalternativen, die grösser als ISO-Container und für die Anforderungen des CO_2-Transports geeignet sind	1
	Ermöglichung eines ersten Pilotprojekts für die lokale CO_2-Speicherung vor 2030, um die Kapazitäten und das Fachwissen der Schweiz zu diesem Thema aufzubauen und weitere Möglichkeiten in diesem Sektor zu fördern.	1
Planning of infrastructures	(Öffentliche) Bereitstellung der CO_2-Transport-Infrastruktur innerhalb der Schweiz, ähnlich wie das Strassennetz	6
	Planung von Infrastrukturen von gemeinsamem Interesse, wie z.B. Zwischenlager in Basel	1
	Identifizierung der wichtigsten Infrastrukturen von gemeinsamem Interesse, die die Kosten senken und/oder den Transport von CO_2 ermöglichen.	1
	Sicherung von Platz / Umschlagsanlagen an Bahnhöfen (Pipeline zum Bhf) resp. Erstellung von Anschlussgleisen zum Emittenten (wo möglich). Koordination der Umschlagsstellen Schiene --> Pipeline	1
	Koordinierte CO_2-Anbindung im Ausland	1
Public relations	Es braucht politische und gesellschaftliche Akzeptanz. Ein Schwerpunkt sollte hier auf Kommunikation und Meinungsbildung liegen.	3
	Frühzeitiges Stakeholderengagement in Gemeinden, in denen CO_2 Speicherung durchgeführt wird	1