INTERIM SYNTHESIS REPORT: INCENTIVES AND FRAMEWORK CONDITIONS FOR CCUS IN SWITZERLAND

DeCIRRA Subproject 3

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Summary

This interim report on sub-project 3 (SP3) of the Innosuisse flagship project DeCIRRA (Decarbonisation of CIties and Regions with Renewable gAses) shows the project status after one and a half years of the four-year project. SP3 aims to contribute to the decarbonisation of Switzerland, in particular with regard to Carbon Dioxide Removal (CDR) and Negative Emission Technologies (NET), as well as Carbon Capture and Storage (CCS) and the utilization of captured CO_2 in products (CCU). While the other sub-projects are of a technical nature, SP3 is more interdisciplinary and has an economic view of the technologies in addition to the technical one, taking into account both technical carbon capture and utilisation/storage (CCUS) and biological methods, e.g. the use of wood (TCCS), biomass (BECCS) and biochar. In addition, SP3 also aims to identify and bring together the key players for decarbonisation in Switzerland in order to disseminate knowledge about CDR and NET and thus support faster scaling of the best technologies.

In the first year, SP3 was primarily concerned with the following tasks: Studying the literature, recording and quantifying the project results that already exist in Switzerland as well as the technologies that will be useful for Switzerland, identifying the important players and stakeholders, building a network and bringing together the relevant players, and deepening and disseminating knowledge among the players. In the second year, the current CDR projects were then analysed and stakeholders were asked about their roles, cooperation, importance and attitudes. Furthermore, the necessary policies for implementation were identified and analysed. This work was accompanied by three master's theses.

For each of the main CCUS technologies identified, this report contains a general description and a life cycle analysis of the system boundaries and material flows. Risks and opportunities, e.g., in the form of co-benefits, costs and potentials, as well as the most important players, existing national and international policies and accounting rules under various accounting frameworks (e.g., international climate regime, national legislation and the overlaps with the voluntary market) are analysed. In addition, findings related to the CO_2 transport infrastructure and the storage of CO_2 are described in separate chapters, as they are relevant for several of the technologies.

A separate chapter takes a more detailed look at the relevant actors and their policy preferences across CCUS technologies, which we gathered through an online survey. Four types of actors are distinguished: The major point source emitters (e.g., cement plants), suppliers of NET services and technologies (e.g., operators of biochar plants), regulators (e.g., FOEN) and other service and support providers accompanying NET /CCUS (such as research institutions, consulting companies, media). A total of 139 stakeholders took part in our survey on the role of NETs. At least one of the NETs is already very relevant for all of the stakeholders surveyed. BECCS was categorised as highly relevant by approx. 25% of the stakeholders and is therefore regarded as the most important NET for Switzerland.

Among the stakeholders surveyed, the federal offices (FOEN and SFOE) were considered to be particularly important for Swiss CDR policy; the waste incineration plants, the Federal Institutes of Technology and politicians were also mentioned particularly often. These players are very active, well connected and play an important role in advancing the technologies. The cement industry is also seen as an important player, although networking and integration should be further expanded here.

For an overview of relevant current and completed projects in the field of NET and CDR, 140 projects were evaluated and categorised, based primarily on the ARAMIS database. Most projects were found on the topic of carbon point capture, followed by biochar and other biological methods. Around 20 projects deal with CO_2 utilisation (CCU).

In order to better assess the acceptance and benefits of policy instruments to support NET/CCS technologies in the short (2030) and long term (2050), the previously identified stakeholders were asked about their preferences with regard to policies for each of the following technologies: TCCS, Biochar, BECCS, CCS/CCU and biological methods. Specifically, they were asked to rank the following 6 policies in order of suitability: CO_2 price; tradable removal certificates (these were defined as offset credits);

exemption from CO_2 levy; tax credits; contracts with price guarantee and binding targets. Overall, the survey, in which around 140 people took part, revealed a broad consensus across all technologies that a CO_2 price - whether through a levy or an emissions trading system - is a key political instrument for advancing NET technologies in Switzerland. This was favoured above all by the technology manufacturers. In second place were binding targets, which were specifically favoured by the regulators. Surprisingly, tax credits were rated as less attractive, although they are a key instrument of climate policy in the USA and Canada. Other important funding instruments were mentioned in the workshop and in the open questions: Subsidies, especially for research, pilot and demonstration projects and funding support.

An important aim of the project was to understand the potential and costs of the analysed technologies in order to plan an optimal Swiss mix and derive a kind of "pseudo merit order" or "CO_2 removal cost curve". The potential and cost information was mainly taken from the literature, whereby the data variance and uncertainties proved to be very high. It is therefore important to ensure support from the project’s praxis partners to compare this data with information from their own plants and pilot projects in the further course of the project.

In addition, scenarios will be developed in the next step within SP3, as this is the only way to map the great complexity and generate meaningful results for different technology combinations. This is very important as a supplement to the "pseudo merit order" which only considers the technologies individually, because in reality the potential of one technology is influenced by the others, for example through the dependence on the same resources. The necessary assumptions for scenario selection will be developed together with the stakeholders in the next workshop. Finally, it has been shown that the accounting or creditability of negative emissions or avoided emissions at the various levels (national inventory, project level) is a major challenge that will be further analysed in the course of the project. In particular, the system boundaries between the voluntary and the mandatory market, but also the country boundaries and the boundaries for the processing of wood, for example, must be clearly defined and, of course, international guidelines, e.g. from the Paris Agreement, must be observed.

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Acronyms and abbreviations

AER	Federal Office for Spatial Development
AFOLU	Agriculture, Forestry, and Land-use
BECCS	Bioenergy with Carbon Capture and Storage
BFH	Bern University of Applied Sciences
CAPEX	Capital expenditures
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CDR	Carbon Dioxide Removal
CH_4	Methane
CHP	Combined heat and power plant
CO_2	Carbon dioxide
DA(C)C	Direct Air (Carbon) Capture
DACCS	Direct Air Carbon Capture and Storage
DACH	Germany, Austria and Switzerland (Deutschland, Österreich, Schweiz)
DeCIRRA	Decarbonization of Cities and Regions with Renewable Gases
DETEC	Federal Department of the Environment, Transport, Energy and Communications
DM	Dry matter
EBC	European Biochar Certification
Empa	Swiss Federal Laboratories for Materials Science and Technology
e-NG	Renewable synthetic methane
EPD	Environmental Product Declaration
ETHZ / ETH Zurich	Federal Institute of Technology Zurich
ETS	Emissions Trading Scheme
EU ETS	European Emissions Trading Scheme
FDFA	Federal Department of Foreign Affairs
Fibl	Research Institute of Organic Agriculture
FLh	Full load hours
FOAG	Federal Office for Agriculture
FOEN	Federal Office of Energy
FOT	Federal Office of Transport
FPI	Federal Pipelines Inspectorate
FSC	Forest Stewardship Council
GHG	Greenhouse gas
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
IgCC	International Green Construction Code
IPCC	Intergovernmental Panel on Climate Change
ITMO	Internationally Transferred Mitigation Outcome
IWB	Energy, water and telecommunications utility in Basel
KIG	Federal law on climate protection goals, innovation and strengthening of energy security
KliK	Foundation for Climate Protection and CO_2 Compensation
LCA	Lifecycle assessment
L-DAC	Liquid Direct Air Capture
LEED	Leadership in Energy and Environmental Design Program
LULUCF	Land use, land-use change and forestry
MFH	Multi-family houses (Apartment blocks)
MRV	Monitoring, Reporting and Verification
NET	Negative Emission Technology
OGE	Open Grid Europe
OPEX	Operational expenditures
PAHs	Polycyclic aromatic hydrocarbons
PCI	Projects of Common Interest

PEFC	Program for Endorsement of Forest Certification
PSA	Pressure swing adsorption
PSI	Paul Scherrer Institute
PtX	Power-to-X
PV	Photovoltaic
SFOE	Swiss Federal Office of the Environment
S-DAC	Solid Direct Air Capture
STEM	Swiss TIMES Energy Systems Model
TCCS	Timber Carbon Capture and Storage
TRL	Technology Readiness Level
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
WIP WtE	Waste incineration plants Waste-to-Energy plants
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research
WWTP	Wastewater treatment plant
ZHAW	Zurich University of Applied Sciences

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1 Introduction

1.1 Background

The Swiss Climate Protection Act (Schweizerische Eidgenossenschaft 2022) 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 emissions that are difficult to avoid.

The focus of sub-project 3 of the project **De**carbonisation of **CI**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 Carbon Capture and Utilisation/Storage (CCUS), i.e., the capture of CO_2 from point sources such as waste incineration plants. With CCUS, the captured CO_2 emissions are either stored (CCS) or utilised (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. In the following report we will use the abbreviations CCUS and CDR, which also includes NET. Whether CCU and CCS can be considered neutral depends very much on the product or storage facility, whether the CO_2 is stored and, if so, for how long. 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), although the requirements for measures relating to re-emissions are still being developed as part of the UN Article 6.4 mechanism (UNFCCC 2023), so that adjustments are to be expected.

The main difference between CCS and NET is therefore that the former prevents additional CO_2 pollution of 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 Federal Council (2022) has determined that to achieve its net-zero target, Switzerland would have to use NET to offset around 7 million t CO_2 per year from agriculture, the waste sector and industry that are otherwise difficult to avoid. Of these, 2 million tonnes are planned domestically and a further 5 million tonnes abroad. An additional 5 million t 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 million t CO_2 per year by 2050 (Panos et al. 2021).

The aim of this interim synthesis report is to:

1. summarise the state of knowledge of the research and implementation partners of DeCIRRA sub-project 3 and relevant external experts in the field of CCUS and CDR,
2. identify gaps in knowledge and derive open research questions from this, and
3. building on these, provide an outlook for further research priorities in 2023-25.

Four different measures will be comprehensively analysed as part of sub-project 3:

1. CO_2 storage in biochar,
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 measures, CO_2 transport with a focus on CO_2 pipelines and CO_2 storage are considered in separate chapters, 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.

1.2 Aim of SP3

The aim of SP3 is to estimate the **sustainably realisable potential** for CCUS and CDR 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 (Bundesrat 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" (Bundesrat 2020, p. 13).

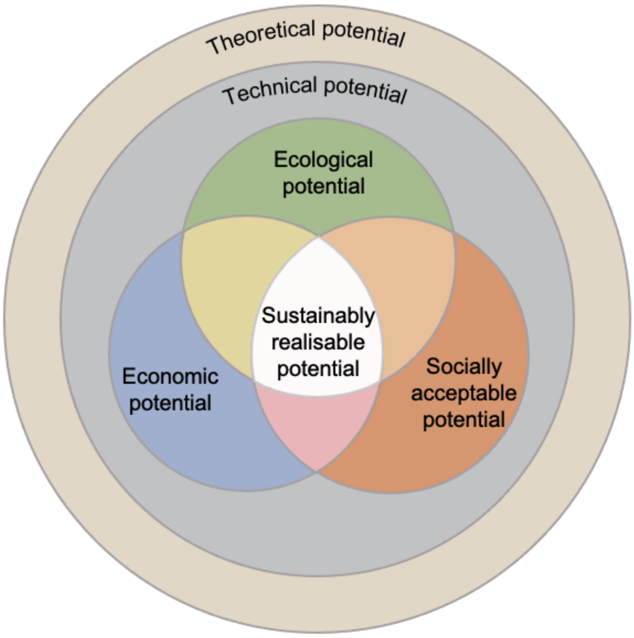

Figure 1: Definition of the sustainably realisable potential

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 CCUS,
    b. **timing** of investments
2. Which **stakeholders** have to be involved in planning and implementing different CCUS and CDR approaches 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 CCUS and CDR 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 CCUS and CDR approaches and what gaps and obstacles exist and could be filled by additional regulations to achieve viable business models and investments for efficient CCUS and CDR 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 CCUS and CDR technologies, policies and financial support mechanisms are **supported by the general public** in Switzerland and how might various financing mechanisms and framings (incl. regarding their distributive impacts) affect public acceptance?

1.3 Scope and structure of the interim synthesis report

The interim synthesis report aims to summarise the status-quo of the research questions listed under A and B in Section 1.2, the questions with regard to social potential will only be included in the final report.

For each CCUS and CDR approach four areas will be examined, namely a) technology, b) accounting, c) actor mapping, and d) policy screening.

Technology: For the four identified technologies and approaches relevant information on the technical and financial information (investment and operation cost) mainly based on existing literature are summarized. For some approaches like TCCS the additional costs of wood construction compared to conventional buildings are used and for DACCS a full cost approach is used. As biochar and BECCS produce different products/services like electricity and/or heat or biochar as such in addition to the captured CO_2 different approaches are discussed 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 like negative environmental side-effects** as well as investment barriers and risks they may face.

Accounting: The report examines three forms of accounting which are important to understand investment incentives for investors, environmental integrity and the tracking and quantification of expected and achieved mitigation results: 1) Life Cycle Assessment (LCA), 2) accounting in national GHG inventories, and 3) the methodologies used to quantify mitigation results in carbon markets.

LCA 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 removal of CO_2 or a relative reduction in emissions of CO_2e. 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 it requires 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 national greenhouse gas inventories and 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 allows to derive incentives for countries to support specific CDR and CCUS 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 obligated to follow these and produce regularly updated inventories of their GHG flows. However, what is reported does not mean that is can be accounted for compliance. For example, under the Kyoto Protocol harvested wood products were reported in a specific line of the inventory but were not able to 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. Where CCUS and CDR activities involve transport of biomass (by way of a harvested wood product) across a national border this should also be consistently reflected in both countries' inventory. 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.

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 of actually achieved emissions reductions or CO_2-removal 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 achieve mitigation results that can be traded as carbon market credits (in case of Article 6.2 these are called "internationally transferred mitigation outcomes"). Hence, accounting here also provides information on the incentives to invest in certain CCUS and/ CDR projects.

Actor mapping: Actors for each of the CCUS and CDR approaches where identified, structured according to their role. This allowed to develop a comprehensive **actor's map**, which is also available in an interactive mode. This allows to understand who are the stakeholders and groups that are relevant for implementing each of the CCUS and CDR approaches.

Policy screening: For each of the CCUS and CDR approaches a first 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). Additionally, insights gained from the DeCIRRA Workshop on Pseudo-Merit Order and Policies and Measures that took place on 10 May 2023 are analysed also in Section 3.3. This contributes to identify regulatory gaps in the outlook section, which will be the focus of the next project phase. The policies and regulations are mapped to different types (e.g. markets, standards) and evaluated along a set of criteria to be developed (e.g. efficiency, effectiveness).

At the end the report includes an outlook (Section 4) which summarises the identified gaps and next steps.

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.

1.4.1 Knowledge building and exchange processes

The DeCIRRA SP3 consortium consists of four research and ten implementation partners. It was therefore necessary to establish processes to ensure the exchange of knowledge between the various partners. The following processes are used for exchange within the project and with external experts:

- Expert discussions
  - The scientific project partners held various technical discussions with individual implementation partners and experts outside the project. 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[1] 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.[2]
  - An Excel file with information on relevant stakeholders and projects was developed and is updated on an ongoing basis.
  - A shared One-Drive was created, although not all partners can 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's theses have already been finalised:

- 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 supervised:

- 2022: Public perception of negative emissions technologies in Switzerland - An analysis based on a quantitative survey, by Daria Sutter.

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[1] https://miro.com/

[2] https://www.zotero.org/

- 2023: The media discourse on negative emission technologies (NET) in Switzerland, by Maurin Forster.

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 databank, which can then be cited directly in project reports and publications. In the course of the first 1.5 years, over 350 publications were viewed and classified.
- Surveys
    - As part of the Master's thesis "Negative Emission Technologies: Swiss Actor Network and Attitudes to Policies", a large 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.
    - As a preliminary study on the topic of acceptance, 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.
- Interviews
    - Many qualitative interviews were conducted with NET experts as part of the master's theses. These were recorded, transcribed and can be found in the master'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

The following events, meetings and workshops have been carried out or visited so far, or are currently being planned:

Table 1: 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	DeCIRRA SP3 and guests
	NET networking event	Exchange with other large projects on NET, including DemoUp Carma, CDR Speed2zero, ZCMA…	
End of July	Report milestone 1	Coordination and finalisation of the milestone report	
Autumn 2023	Meeting on timber construction accounting	Exchange on standards for timber construction, e.g., Verra	
Autumn 2023	Scenario workshop with ETHZ	Preparation and exchange over the possible scenarios and methods	ETH, DeCIRRA SP3, other experts
Winter 2023	Inventory accounting workshop (online)	Preparation of inventory and accounting methods	
Jan 2024	SP3 update	Meeting to bring together the latest findings	

1.5 Definitions of terms

The following definitions were obtained mostly 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. Biochar is distinguished from charcoal by its application: biochar is used as a soil amendment with the intention to improve soil functions and to reduce greenhouse gas emissions from biomass that would otherwise decompose rapidly.[3] Abbreviation can also be BCR.

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

Bioenergy with carbon dioxide capture and storage (BECCS): 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.

Carbon dioxide capture and storage (CCS): 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.

Carbon dioxide capture and utilisation (CCU): 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.

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.

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.

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).

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

Lifecycle assessment (LCA): Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product or service throughout its lifecycle.[4]

Net-zero greenhouse gas emissions: Condition in which metric weighted anthropogenic greenhouse gas (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.

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

[4] See also the ISO 14044 standard: https://www.iso.org/standard/38498.html.

Net-zero emissions (Schweizerische Eidgenossenschaft 2022 Art. 2): largest possible reduction of greenhouse gas emissions and compensation of the impact of remaining emissions through the use of negative emission technologies.

Negative emissions technologies (NET) (Schweizerische Eidgenossenschaft 2022 Art. 2): biological and technical processes to remove CO_2 from the atmosphere and bind it permanently in forests, soils, wood products or other carbon reservoirs.

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).

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 standardized 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.

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.

2 Analysis of biological and technical CCUS options

2.1 Overview over system boundaries for quantification of emissions and other environmental burdens

Despite of the fact that specific CDR methods can substantially differ in their nature (Figure 2) (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).

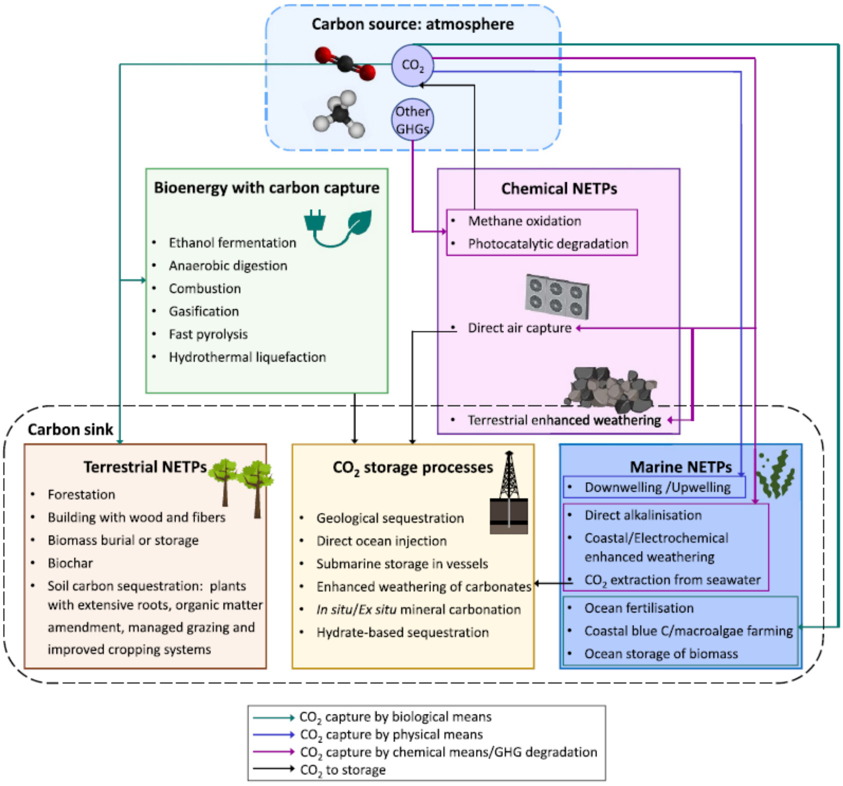

Figure 2: Overview of CDR methods and CO_2 sequestration processes (Cobo et al. 2023).

Environmental Life Cycle Assessment (LCA) can be considered as 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. Some ambiguity exists regarding the extent to which temporary CO_2 removal from the atmosphere – often due to carbon capture and utilisation (CCU) processes – can and should be considered as effective CDR and which climate benefits can and should be assigned to it. Key issue in this context is the time period for which CO_2 is temporarily stored and removed from the atmosphere (so called permanence) 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). Most often, CO_2 which is stored for 100 years or more by CCU or in other ways, is considered to be "permanently removed", i.e. associated with a global warming potential (GWP) and climate impacts of zero (de Kleijne et al. 2022; Terlouw, Bauer, et al. 2021).

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 and 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 case of wood as construction material (TCCS) and energy supply in 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 chapters for each of the approaches.

2.2 Biochar

2.2.1 General description

Biochar is a valuable carbon-rich material that is obtained from organic biomass via carbonisation without oxygen. Because plants bind CO_2 from the air, biochar production allows removing CO_2 from the air and storing it. Around half of the carbon in the biomass is converted into biochar, which is extremely stable depending on the processing temperature, hardly degrades biologically or chemically and can therefore be stored well in the soil. If biochar is introduced into the soil, **a carbon sink with a half-life of up to 460 years** can be created, although lower values are found depending on the study, production process and starting substance.[5]

Thanks to its porous nature and resulting large surface area, biochar also has other advantages. For example, as a water and nutrient carrier it can improve soil fertility or reduce methane or nitrous oxide emissions in agriculture. These co-benefits are explained in more detail in a separate chapter. If the biomass is not processed into biochar or otherwise, it disintegrates, and the carbon is released back into the atmosphere as CO_2 via decomposition and methane via fermentation. It therefore appears to be a very sensible measure to avoid this natural decomposition process and to continue to store the carbon in a more stable form.

Terminology and production processes

If biochar is obtained as a by-product of a heat generation or biomass-to-energy plant, then it is referred to as CCUS (this is for example the case of the E360 plants, which are electricity-led). However, if biochar is produced as the main product, then it is categorised worldwide, including by the IPCC, as a CCS or CDR technology. Both definitions are used in this report, depending on the application. Biochar production technologies have become increasingly important in recent years, as biochar is comparatively easy to produce.

Production takes place via **pyrolysis** or **hydrothermal carbonisation (HTC)**. **HTC** is a thermochemical conversion process in which biomass is exposed to high temperatures (approx. 300-450°) and pressures in the presence of water. This technology mimics the natural carbon formation process, but in a much shorter time frame. During HTC, the biomass undergoes various chemical reactions, including hydrolysis, dehydration and polymerisation, resulting in the formation of a solid carbon-rich material known as hydrochar. HTC offers several advantages, such as the ability to process a variety of feedstocks, but especially liquid biomass from, e.g., sewage sludge or wastewater, and the potential to produce biochar with improved nutrient retention (Röhrdanz et al. 2019).

Pyrolysis, on the other hand, is a thermal decomposition process that takes place in the absence of oxygen. Biomass is heated to high temperatures, typically between 450°C and 950°C, which leads to the release of volatile compounds and the formation of biochar as a solid residue. Pyrolysis can be categorised into three main types: slow pyrolysis, fast pyrolysis and gasification. Slow pyrolysis involves slow heating rates and longer residence times, resulting in a higher biochar yield. Fast pyrolysis uses fast heating rates, resulting in higher production of bio-oil along with biochar. Gasification is a partial combustion process that produces a synthesis gas (syngas) of carbon monoxide, hydrogen and other gases and biochar as a by-product. Depending on the technology, additional electricity, heat and pyrolysis oil (by-products) can be obtained during the process, which significantly determine the economic efficiency. The choice between these technologies depends on factors such as the properties and available quantity of the source materials (such as forestry residues), the desired utilisation properties of the biochar, and the availability of suitable infrastructure.

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, shrubs, grasses, 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

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[5] https://www.biochar-industry.com/biochar/

or solids from animals or human faeces (sewage sludge) and waste biomass consist 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 (EBC 2020) publishes the following positive list[6] of authorised biomass raw materials for the production of biochar in the EU, which is also used in Switzerland.

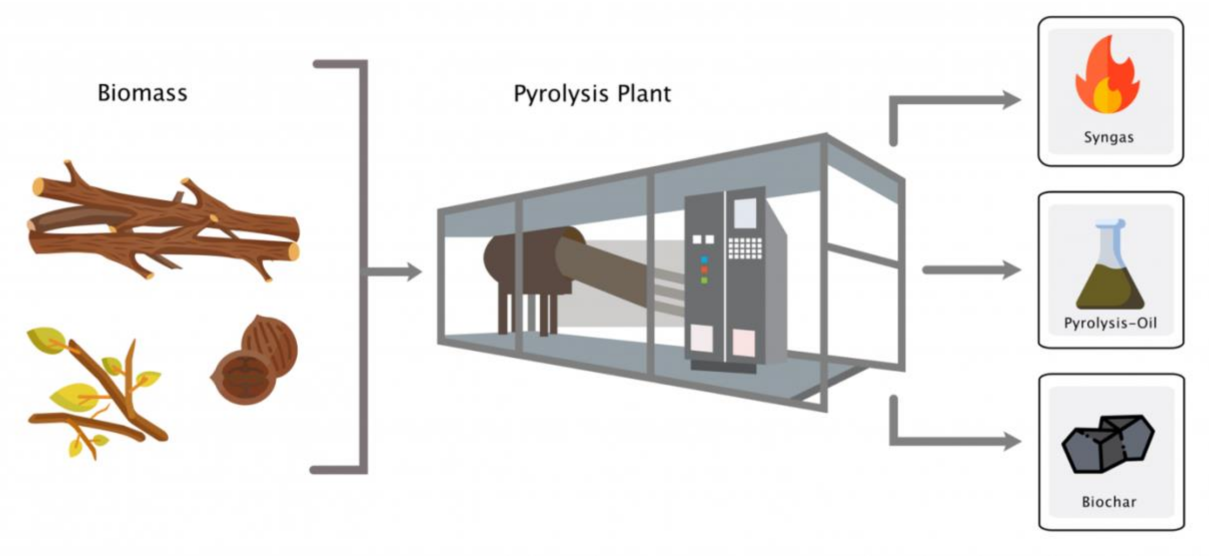

Figure 3: Pyrolysis process (https://www.biochar-industry.com/biochar/)

The **quality** of the biochar 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. Modern pyrolysis plants grind the pyrolysis material using sophisticated grinding technology in order to produce the largest possible reactive surface area and thus increase the biochar's effectiveness or even enable it to be applied to the fields in liquid form. There are now also a number of pilot projects in the HTC area, where experience is being gathered on the quality of the biochar (Mehli et al. 2021).

Applications

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. In the future, it could be used as fuel.

In **agricultural applications**, 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 and not only carbon added to the soil, but other co-benefits can also be achieved.

Other important applications are in **landscape gardening**, where nutrient-enriched biochar is incorporated into the soil, serving as compost, fertiliser or as a water-storing substrate for urban trees, while also creating a carbon sink in the soil.

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[6] https://www.european-biochar.org/media/doc/2/positivlist_en_2022_1_v10_1.pdf

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:

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) 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[7] and Inkoh[8]. The latest, so-called "fully integrated" plant is operated by 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[9]. Only material-led plant technologies are used. The latest developments are moving towards even smaller (farm) units. How quality can be ensured here still needs to be regulated.

The category of manufacturer is largely dependent on the technology used. Below is an illustration from system manufacturer BIOMACON GmbH[10], 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.

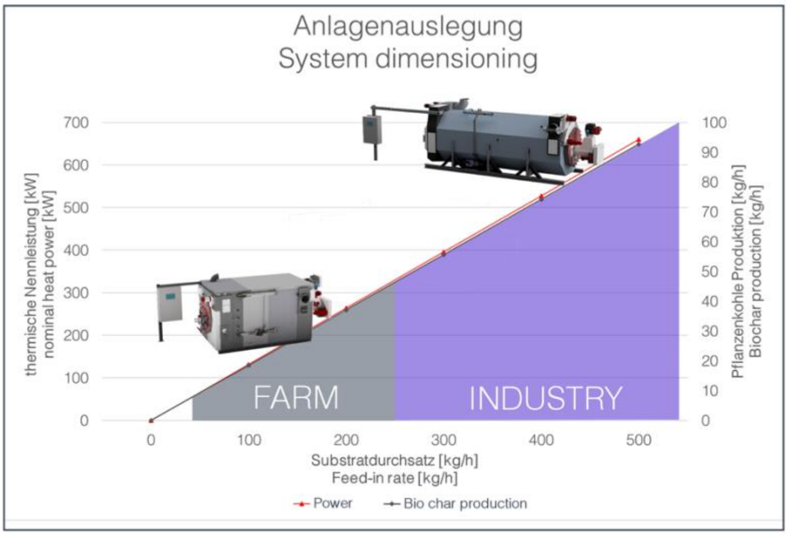

Figure 4: Biochar production plants (https://www.biomacon.com/)

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[7] https://lignocarbon.ch/

[8] https://inkoh.swiss/

[9] http://www.verora.ch/, https://www.a-p-d.ch/pflanzenkohle/

[10] https://www.biomacon.com/

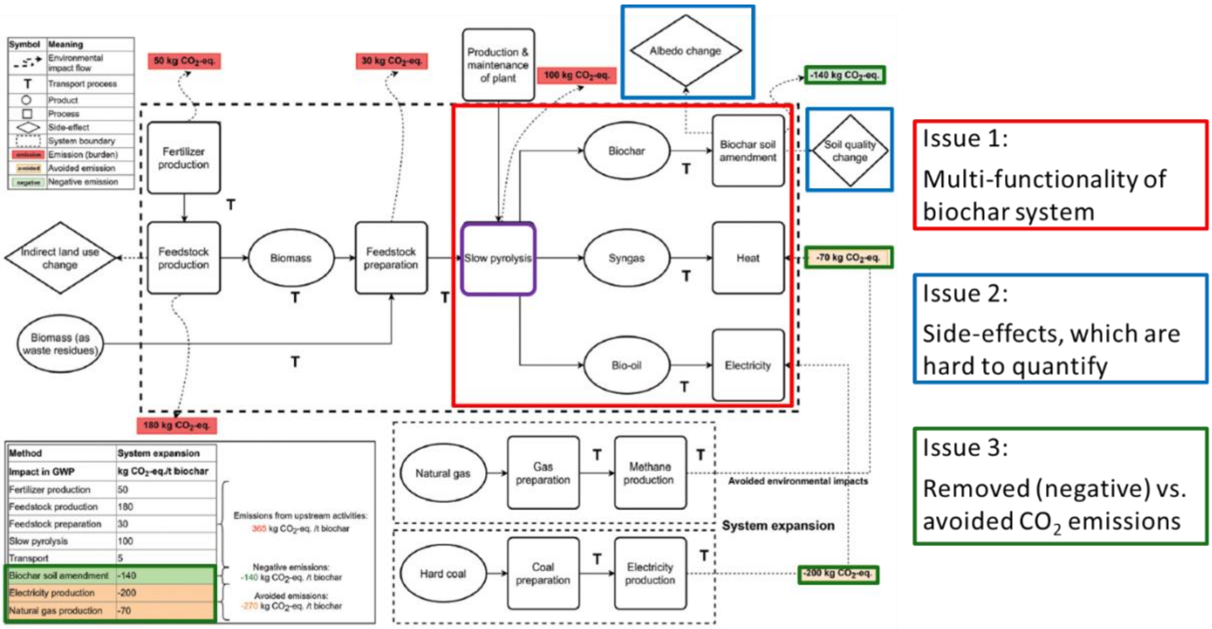
2.2.2 System boundaries, material and emissions flows, and main drivers

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 greenhouse gases 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 provided to external users. Figure 5 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.



Method	System expansion
Impact in GWP	kg CO_2-eq./t biochar
Fertilizer production	50
Feedstock production	180
Feedstock preparation	30
Slow pyrolysis	100
Transport	5
Biochar soil amendment	-140
Electricity production	-200
Natural gas production	-70

Figure 5: Exemplary process system of a typical biochar-to-soil process chain, visualizing key issues in the (carbon) accounting; adapted from Terlouw et al. (2021).

Multi-functionality of the biochar production process can be dealt with in different ways: One option is to assign (“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.

Such avoided environmental burdens (especially climate impacts) should always be reported separately from the carbon removal due to biochar production and application (Terlouw, Bauer, et al. 2021), regarding 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 of 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.

2.2.3 Co-benefits

Alongside timber construction with its substitution effects, biochar is one of the few NETs with additional co-benefits. These were examined in detail in a detailed 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 emission of greenhouse gases, 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% (Bundesrat 2023). 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

- Reduction of nitrous oxide emissions from the soil
- 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
- Promotion of root formation, thereby improving phosphorus uptake

- 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
- Easier recovery of valuable resources such as phosphorus and nitrogen (HTC)
- High-quality 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.

It is also important that biochar should only be produced where 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.

2.2.4 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). The FOEN has published a fact sheet on this topic (Bundesamt für Umwelt (BAFU) et al. 2023). The most important risks are summarised below (Haubold-Rosar et al. 2016; Xiang et al. 2021).

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. 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 only industrial plants can afford (Haubold-Rosar et al. 2016).

Soil pH, nutrient imbalances and ecotoxicity
Pyrolysis charcoals usually have pH values above 7 and can lead to alkalisation and increased acid buffering in treated soils. Thus, the alkaline character of biochar can change the pH value of the soil. Excessive or improper application of biochar can impair soil fertility and nutrient availability. In addition, biochar can bind nutrients and hinder their release (Haubold-Rosar et al. 2016). Biochar can have a potentially ecotoxic effect, e.g., on earthworms or microorganisms.

Carbon emissions
The production of biochar requires energy in the form of heat (usually own waste heat) and electricity (material transport) in addition to the mostly fossil-based material transport to and from the plant. If this energy comes from fossil fuels, it can contribute to greenhouse gas emissions and exacerbate climate change. In addition, improper pyrolysis processes or biochar utilisation 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 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 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 t CO_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 recovers 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. For example, the plants have to be repeatedly shut down in order to optimise processes. It was therefore not possible for us to obtain specific Swiss production costs, as these currently fluctuate too much and are dominated by the high maintenance and installation costs. However, it is expected that this will change in the next few years and that reliable data on manufacturing costs will then be available (Mehli et al. 2021). This will be a main focus in the further course of SP3.

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

A) **Costs** for the production of one tonne of biochar (storage of one tonne of CO_2):

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/t CO_2 and CHF 10/t CO_2 for the year 2050. Other studies have estimated the costs at 10-135 CHF/t CO_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. New laws require a land register entry for use on agricultural land; these costs vary depending on the municipality, but also represent an administrative hurdle in addition to a financial one. Further research is needed here.

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

In Switzerland, 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. Internet research on sales portals shows the following current market prices for biochar:

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.

Potentials

Biochar has already reached the practical application stage (TRL 9) in terms of the production process, but the availability of pyrolysis plants and biomass is currently still limited. A detailed article on this can be found in the CDR Report of the Risk Dialogue Foundation on pages 41-42 (Beuttler et al. 2019). According to this report, the maximum market volume is 600’000 tonnes of biochar per year which allows to sequester 2.2. Mt CO_{2e}, while 900’000 tonnes per year could be produced, i.e., more than the market is estimated to be able to absorb. The assumption is that the application is in total free of costs or even at negative costs given high co-benefits. Nevertheless, thanks to other positive co-benefits and e.g. the substitution of light heating oil, this volume of biochar could offset around 18% of Swiss emissions. In a more recent study, Brunner und Knutti (2022) estimate the direct sequestration potential if biochar at 1.5 Mt $CO_{2e.}$

Utilisation potential

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 hampered by two regulations: biochar for soil improvement is legally classified as fertiliser and the quantity of 8 tonnes per hectare and period may not be exceeded (Bundesrat 2012, Annex 3). In addition, registration in the land register is required for certification (Bundesrat 2012, Art. 8a; see also Bundesamt für Umwelt (BAFU) 2021), a more or less complex and expensive measure depending on the canton, which deters many farmers.

The geological storage of biochar as a CO_2 sink is not currently being discussed (Cames et al. 2023). The use of biochar 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 biochar 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

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[11] https://kohlenkraft.ch/

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]

One obstacle to the rapid scaling of biochar production is the limited availability of source materials, especially when it comes to wood. Biomass is currently in high demand as an energy source and demand is set to increase in the future as part of the decarbonisation of the heating market. Biomass makes it possible to replace fossil fuels such as coal, oil or gas for heat generation. Biomass from residual crown material is in particularly high demand for forest wood chips and competes with its use as a source material for biochar for agricultural applications. Roundwood for timber construction will only compete with biochar if log prices continue to fall. Wood is generally in great demand as a raw material because it is relatively dry and can be easily transported and stored.

The widely recognised cascade use of biomass also calls for wood to be used primarily first in construction and only later, after deconstruction, for the production of biochar or for thermal utilisation.

Production potential in 2030

To estimate the potential of biochar production for Switzerland, the sustainably available potential of suitable biomass that does not compete with other uses must be estimated. According to Thees et al., the biomass sources are divided into woody and non-woody biomass and a potential of 2.8 million tonnes of dry matter (DM) (= 44.2 petajoules) per year is calculated for Switzerland in addition to the already used biomass (Thees et al. 2017).

The following calculation can be used to estimate the amount of CO_2 that can be captured using biochar: We start with the roughly 2.8 million tonnes of dry matter (out of which, 1/3 consists of woody biomass – forest wood, wood from landscape maintenance, wood residues and waste wood). If we round up to 3 million tonnes and assume that the carbon content is around 50% of the dry matter (conservative estimate) and include the efficiency of a pyrolysis plant of 60%, we get 0.9 million tonnes of biochar. If the biochar consists of 100% carbon, the combustion results in 3.3 million tonnes of CO_2 from 0.9 million tonnes of pure carbon (3.6 conversion factor C to CO_2). The stable carbon content, which remains "permanently" in the soil, is approx. 75%. This would result in an annual savings potential or sink potential of approx. 2.25 million tonnes of CO_2.

These figures are consistent with the information provided in a FOEN publication, according to which the savings or sink potential amounts to 2.2 million tonnes of CO_2 per year if all available dry biomass is incorporated into the soil nationwide as biochar (Jakob 2022). The exact potential of large-scale production and use of biochar has not yet been fully clarified. The differences in the calculations are based on different initial conditions and the type of biomass that is used and whether, for example, waste is used or targeted cultivation takes place.

In reality, competition will be fierce, particularly for the one third consisting of woody biomass. Due to its high energy content, woody biomass will be fed almost entirely directly into the heating market by 2030 and tied into long-term contracts, making it available for pyrolysis only to a limited extent. Our implementation partner Thomas Fedrizzi says: "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 CO_2 storage will remain fierce."

Production potential in 2050

It is important to note that the potential for biochar in Switzerland depends on various uncertainties and dynamic factors, such as the goals of our society, how biomass is used, the joint efforts of politicians, researchers and entrepreneurs, as well as the willingness of the agricultural sector to adopt sustainable practices. How much the potential will develop by 2050 is therefore in our hands. For example, human and animal excrement is currently still little utilised and hardly any fast-growing plants are cultivated

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

specifically for the production of biomass. It can therefore be assumed that the available quantities could be significantly increased if the right framework conditions are in place. An estimate can only be made for certain scenarios, which are planned in the next project phase.

Main drivers

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 registry and instead introducing a simple register.
- 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.

2.2.6 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. 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 greenhouse gas 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.

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[13] from the company LOGBAU, for example, is the first concrete in Switzerland to contain biochar and thus store CO_2. Kohlenkraft[14] has pilot projects in the areas of insulation and plaster.

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[13] https://www.klark.swiss/

[14] https://kohlenkraft.ch/

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[15] in Basel.

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.

2.2.7 National and international policies and incentives

In Switzerland

The Swiss government allows the use of biochar for compensating emissions in the transport sector, through its application in agriculture and the construction sector. In the construction sector, biochar can be used both in building materials and as a filling material in the soil.

For compensation projects involving the agricultural use of biochar, in Section 5 and Appendix 3 of its CO_2 Ordinance (Bundesrat 2012), the Swiss government allows only an application of up to 8 tonnes of biochar per hectare of soil if the project is to be eligible to generate certificates (Appendix 3). In addition, such projects have to comply with the Swiss Fertilizer Regulation, the land has to be formally registered in the land register (Article 8a), and it has to be demonstrated that the sequestered CO_2 remains in the soil for at least 30 years (Article 5.2). These requirements and also the published fact sheet (Bundesamt für Umwelt (BAFU) et al. 2023) show that the Swiss government does in principle support biochar projects, however, it has a cautious approach to biochar application, especially for soils.

Nonetheless, the requirements currently in place make biochar projects non-viable under the Swiss compensation scheme. Particularly the requirement to register the land formally in the land register may result in too high transaction costs. 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 pyrolyzed. 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).

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

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[15] https://www.iwb.ch/klimadreh/ratgeber/co2-einsparen/pflanzenkohle

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.

At the international level, nonetheless, biochar projects are traded globally on the voluntary carbon removal market (see Section 2.2.8). In addition, recommendations on how to include removals – including from biochar – in the Article 6.4 mechanism under the Paris Agreement are currently being prepared by the Article 6.4 Supervisory Body (UNFCCC 2023). A decision on this issue is expected at COP28 in Dubai in December 2023. These recommendations and the resulting work on accounting methodologies for removals will set an important precedent for other certification bodies.

2.2.8 Accounting rules

National accounting of biochar

Results of biochar application in agriculture and forestry are to be accounted for in the greenhouse gas 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 350°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.

Project-based MRV of biochar projects

Biochar has the largest market share of all removal project types in the voluntary carbon markets and achieve average prices of 186 $/tCO_2$ (cdr.fyi, 2023). There are a number of programs and standards that offer CDR products on the voluntary carbon market[16]. One of the first programs was offered by First Climate based on the ISO 14-064-2 standard that sold the first 124 t CO_2 removed by biochar in 2019. The voluntary carbon standard Verra released a methodology for biochar utilization in soil and a non-soil application in August 2022. At the same time there are new institutions that develop carbon standards which only focus on CDR, including Puro with its first biochar methodology in May 2019 or CarbonFuture with its C-Sink certification standard related to the European Biochar Certification

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[16] Overview of CO_2 purchases worldwide, https://www.cdr.fyi/, accessed July 17, 2023

(EBC)[17]. 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).

Table 2: Overview of carbon removal standards applicable to biochar (Own work based on the discussion at the DeCIRRA online workshop on 20.03.23)

Standards / Criteria	**Puro.earth**	**Verra Carbon Standard** (voluntary, USA)	**European Biochar Certificate** (voluntary, Europe)	**Swiss CO_2 Ordinance**	**European Union Certification Framework** for Carbon Removals
Allowed use				Fertilizer / Soil application (up to 8 t/hectare per crediting period) After consultation: eventually also construction material	
Allowed raw materials	Sustainable biomass, waste biomass, and biomass grown explicitly for biochar	Specified in the method VM0044	See EBC positive list	Not yet clear; but there are production criteria for biochar in Switzerland	Not yet defined
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	Not yet defined but carbon removal activities expected to go beyond standard practices and legal requirements
Permanence (duration of storage and leakage risk)	100 years	100 years	100 years	100 years	For biochar to be accepted as technical solution, > 1000 years
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	Not yet defined
Transparency (governance, register)	Puro register	Verra register	Carbon Standards International register	FOEN register	Not yet defined
Prevention of double use / doble 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	Not yet defined
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	Not yet defined
Baseline	No project (BAU)	No project (BAU)	No project (BAU)	Not yet clear; depending on the programme; probably no project (BAU)	Not yet defined

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

As shown in Table 2, mainstream standards are beginning to include biochar – following initial work by sector-actors such as the European Biochar Initiative (EBI) and the later introduction of the Puro Earth standard, both of which had initially been criticised for lack of transparency and questionable additionality determination (Poralla et al. 2022). For example, the Verified Carbon Standard (VCS) has now adopted a baseline and MRV methodology for biochar in 2022, which thus allows for the development and monetization of carbon dioxide removal results based on the production, sale, and use of biochar in the world's largest voluntary carbon market and with the requisite transparency and accountability.

2.2.9 Open questions

Addressing the technological aspects surrounding the use of biochar as either an additive in concrete production or for soil carbon enhancements raises some further questions. Firstly, it is important to ascertain which source materials for biochar are suitable for such applications. The impact of using different materials, such as waste wood, could vary in terms of quality, ruling out some source materials as either unsustainable or otherwise problematic. In addition, there is the challenge of measuring the actual carbon-saving benefits reliably at the project level, as the standards vary in regards to the level of detail in determining the carbon content embodied in the biochar as well as the consideration of potential upstream displacement effects (potentially causing second-order emissions from land-use change). Other issues include a need to more systematically categorize the quality of old wood towards use as a source material, exploring additional application pathways to different soil types including perhaps urban infrastructures, and determining the reliability of carbon storage durations for various biochar qualities. The technological nuances involved necessitate scientific inquiry to address these gaps.

Turning to the questions of risks, benefits, costs, and potential drivers, the impact of biochar on soil water retention can be a co-benefit, but its uncertainty is also a source of concern regarding environmental sustainability and agricultural productivity. Understanding this effect across a greater variety of soil types could be instrumental to accelerate its uptake given benefits extending beyond carbon sequestration to other ecosystem services. Quantifying these additional advantages in monetary terms, however, is a complex endeavour. The challenge lies in attributing economic values to co-benefits like soil fertility, water quality, additional to climate mitigation to present a comprehensive cost-benefit analysis for stakeholders.

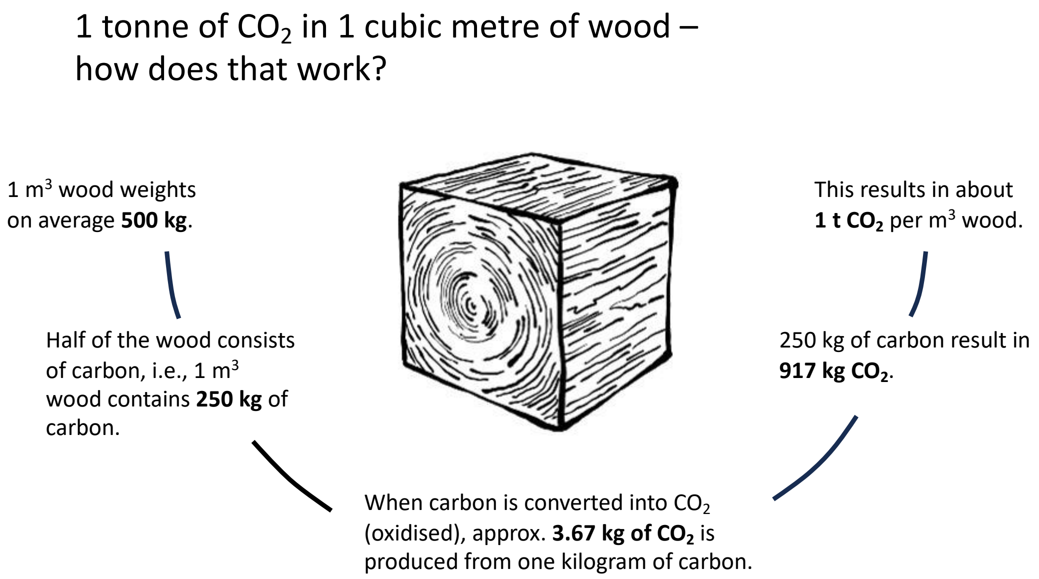
Finally, issues of governance, such as standardization, independent control, and monitoring of biochar production and quality, need attention. Existing sustainability certifications and voluntary carbon market crediting may not comprehensively cover all aspects and the emerging EU certification framework represents an additional question mark as it promises without details to also consider biodiversity and other ecosystem effects in its methodology. Cross-border activities add another layer of complexity, given that biochar soil additions tend not to be consistently accounted for at the national level and therefore challenging the accurate reporting of the carbon flows involved in trans-boundary biomass or biochar transfers under the Paris Agreement and the resulting accuracy in crediting of removals. Moreover, the accounting of non-wood products, such as agricultural residues used for biochar, is an area that has not been fully explored and standardized. These governance-related issues require concerted efforts from actors at various levels—local, national, and international—to ensure that the biochar industry evolves in a sustainable and globally beneficial manner.

2.3 TCCS

2.3.1 General description

The construction sector is responsible for 25% of Switzerland's CO_2 emissions, making it one of the most material- and emissions-intensive sectors in Switzerland and worldwide.[18] Of this, the production of building materials is responsible for around 30% of greenhouse gas emissions (11 Mt CO_2) (Gauch et al. 2016). With wood as a renewable raw material, the use of wood in construction is seen as an opportunity to decarbonise the construction sector and use it as a long-term CO_2 reservoir.

Photosynthesis binds atmospheric CO_2 into carbon 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 6).



1 tonne of CO_2 in 1 cubic metre of wood – how does that work?

1 m^3 wood weights on average **500 kg**.

Half of the wood consists of carbon, i.e., 1 m^3 wood contains **250 kg** of carbon.

When carbon is converted into CO_2 (oxidised), approx. **3.67 kg of CO_2** is produced from one kilogram of carbon.

250 kg of carbon result in **917 kg CO_2**.

This results in about **1 t CO_2** per m^3 wood.

Figure 6: Conversion of the amount of carbon dioxide stored in one cubic metre of wood into carbon (CLB Schweiz GmbH)

If this wood is used, the CO_2 equivalents sequestered in the forest can remain stored in the building and construction material for decades to hundreds of years, depending on the planned service life of the building and the handling of the material when the building is dismantled. If planning is based on circular or cascade utilisation, the timber structure can be reused in the event of demolition or recycled in a cascade. At the time when the timber is burnt, fossil fuels are currently substituted by the heat generated. If BECCS establishes itself as the standard solution, negative emissions are generated at the time of burning. At the same time, emission-intensive alternative building materials such as steel and concrete will also be substituted, thereby reducing emissions from the construction industry.

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 is around 1.2 tonnes per cubic metre compared to softwoods with a CO_2 storage capacity of around 1 tonne, which is why more attention should be paid to hardwood from this point of view in the future. The heat energy (e.g., drying chambers) required to process round timber into construction timber is largely obtained from wood processing by-products, which is why it is considered CO_2-neutral. Electricity for the mechanical processes can be accounted on the basis of the Swiss consumer electricity mix, whereby the large roofs

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[18] https://www.bafu.admin.ch/bafu/de/home/themen/klima/fachinformationen/verminderungsmassnahmen/gebaeude.html

of the plants are increasingly fitted with solar cells, so that the electricity also has hardly any CO_2 emissions. 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 is just as durable – in timber buildings, the carbon sequestered from the atmosphere in the forest can be stored for up to 200 years (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 (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 CO_2 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 CO_2 storage (Savi and Klingler 2022). TCCS is the only CCS or carbon removal approach that achieves not only storage performance because of the long-term use of wood, but also as a substitute material for steel and concrete – which mostly comes from national production due to its considerable weight[19] –, especially in high-performance structural elements such as beams and columns made of hardwood. This substitution effect can vary depending on the technology used in the production of the baseline materials (i.e., steel and concrete). The combination of sequestration, storage and substitution is therefore also referred to internationally as the 3S approach.

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 does not come from primary forests.

In 2021, 208’000 m^3 of sawn timber were processed in Swiss plants into glued laminated timber for construction, which corresponds to an increase of 15% compared to the previous year (2020, 180’869.6 m^3) (Lädrach 2022). It is assumed that around 75% of construction timber is imported (Bundesamt für Umwelt (BAFU) 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 and Eastern Europe.

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

Using wood as load bearing supporting structure construction material allows for (temporary) storage of carbon dioxide up to 100 years and thus removal from the atmosphere. Depending on the end-of-life of wooden construction materials, CO_2 might be emitted to the atmosphere after the lifetime of a building, e.g., if the wood is disposed of in a waste incineration plant. If such a waste incineration might be equipped with CCS in the future, most of this CO_2 would be geologically stored and thus permanently removed from the atmosphere. Regarding climate impacts, or the effective CDR, the time period of CO_2 storage in the wooden construction materials is essential as, in case of release of CO_2 back to the atmosphere after this time period, CO_2 emissions and associated climate impacts can be considered as being delayed or shifted back in time and associated temperature decreases (compared to not using wood as temporary carbon storage) fade as CO_2 is re-emitted, as visualized in a stylized way in Figure 7 (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).

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[19] In Switzerland, over 90% of the gravel and cement used is produced domestically. Most of the reinforcing steel is recycled steel from Gerlafingen SO, which is produced in a relatively CO_2-friendly way using an electric arc furnace.

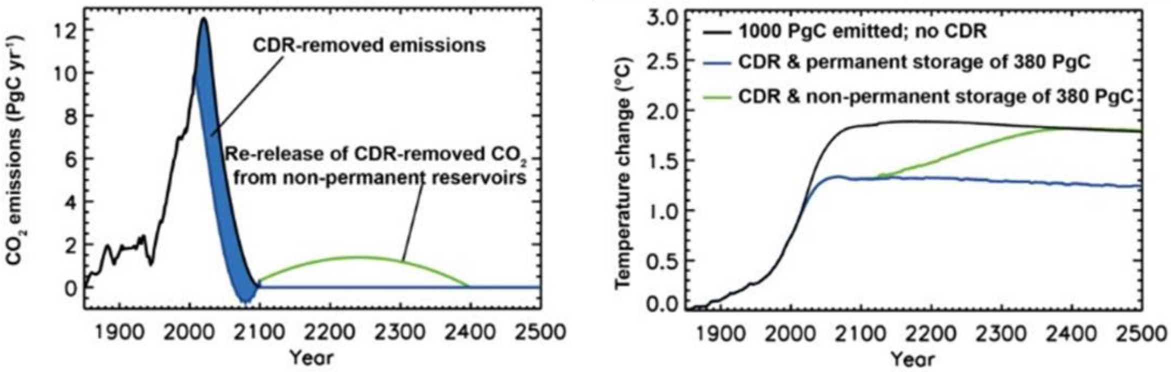

Figure 7: Visualization of (temporary) CO_2 storage and associated temperature effect on a global level for a certain amount of CO_2 (temporarily) stored (Ciais et al. 2014, p. 548).

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 8.

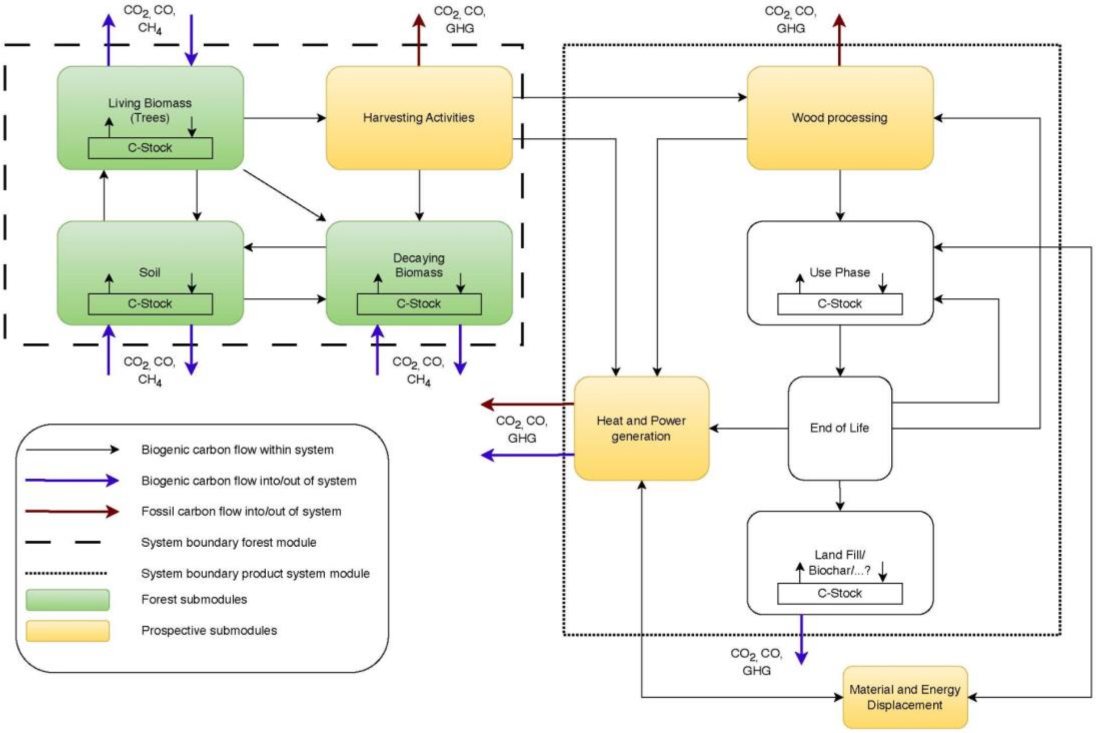

Figure 8: Exemplary process system of a typical TCCS process chain, visualizing key issues in the (carbon) accounting

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 8). 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 replaced materials which may change with the changing energy mix, production technologies for displaced material and potential CCS application in those processes, as well as the emissions associated with wood processing.

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 geographical area, the consequences of its use as construction material instead of other purposes, for example energy generation, need to be taken into account.

Since the end-of-life of buildings built today or in the future is unknown, it is recommended to include several different scenarios in the accounting and to quantify the effect of those. The same holds true for the lifetime of buildings. End-of-life scenarios need to take into account potential “by-products” of disposal, for example energy generation in case wood is burned (Cordier et al. 2022).

If wooden construction materials substitute more traditional materials like concrete, bricks and steel, effects of such substitution in terms of reduced or increased environmental burdens need to be quantified. In general, substituted products can be assumed to be avoided (in terms of their production), and environmental credits 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 would differ. Again, it is important to differentiate between and separately report amounts of CO_2 removed from the atmosphere and potential CO_2 emission reductions due to substitution effects.

Life cycle of a timber building

Figure 9 displays the life cycle of a timber building and the life cycle stages relevant to its carbon footprint.

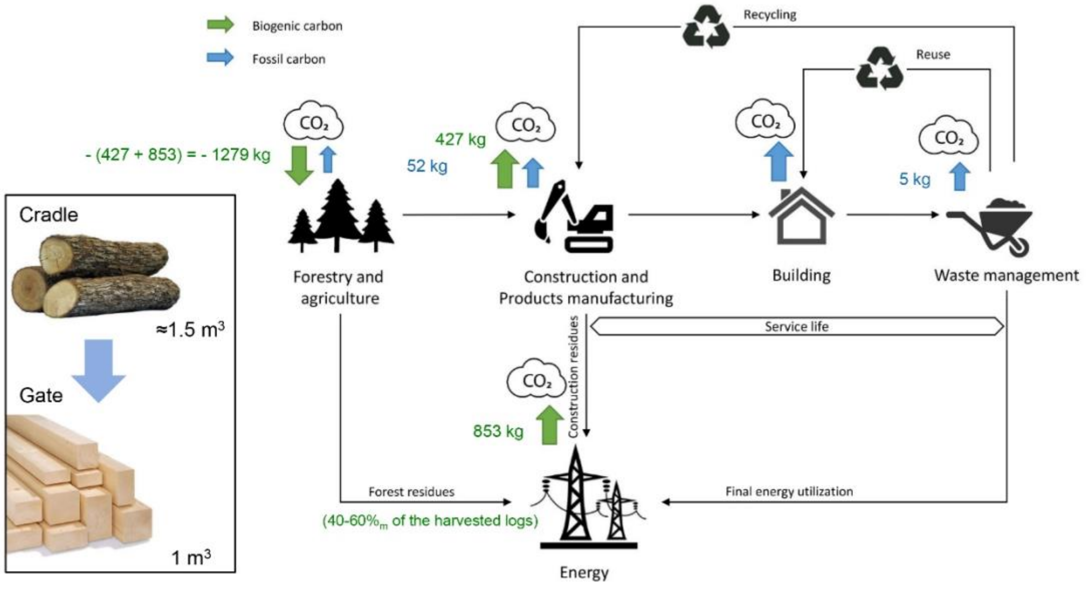

Figure 9: Simplified illustration of the life cycle of a timber construction and the carbon flows generated per life cycle stage (Pittau et al. 2022, p. 15).

Figure 10 compares the greenhouse gas emissions from the production, transport and disposal of 1 m^3 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 greenhouse gas emissions than the one produced in Switzerland. It can be seen that the electricity mix for drying and transport have a strong influence on total emissions. In example 1, transport causes 16% of emissions, in example 3 it causes 35% (Frischknecht and Ramseier 2020).

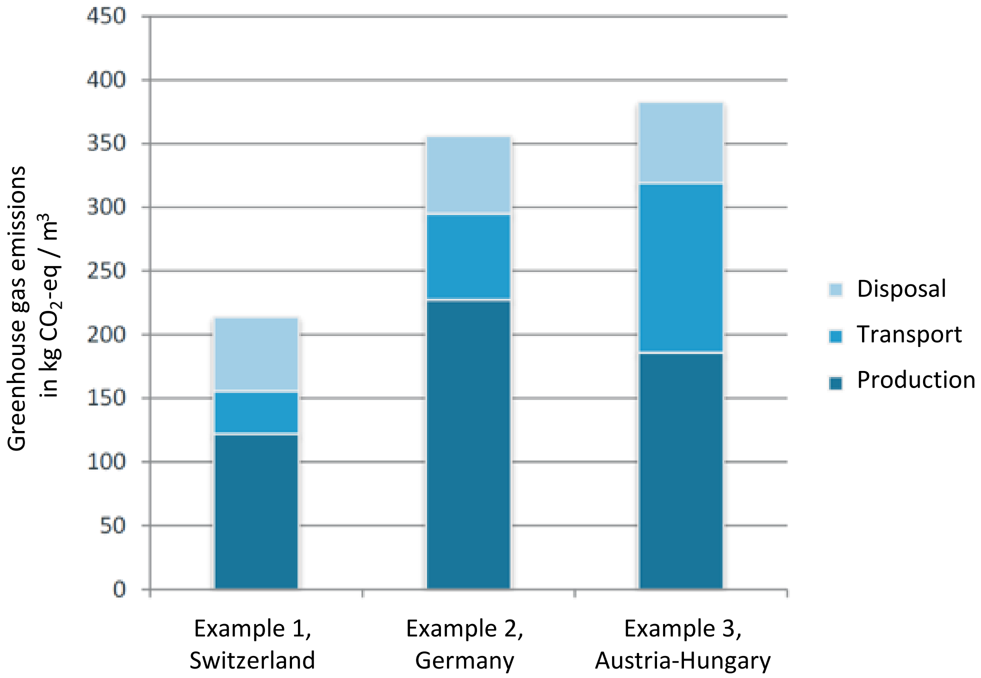

Figure 10: Differences in the GHG emissions caused for 1 m^3 of glued laminated timber produced in Switzerland, Germany and Hungary (Frischknecht and Ramseier 2020, p. 11).

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.

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 never 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 waste wood (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 CO_2-neutral fuels in the vehicle fleet 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[20]). 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.

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

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 poorly developed regions would have to be transported by helicopter, for example. At the same time, 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. Hardwood tends to be dried for longer than softwood. However, as the drying process is either natural or uses residual wood energy, it can be considered CO_2-neutral.

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. 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

Co-benefits of timber construction can be further climate-related co-benefits such as the substitution of other emission-intensive building materials (if this has not already been taken into account), an increase in sink performance through better sustainable forest management and an improvement in the resilience of forests to extreme weather situations. Non-climate-related co-benefits consist of waste avoidance and other environmental co-benefits.

Directly climate-relevant co-benefits

Substitution of other building materials
In addition to the CO_2 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 11 shows 10 case studies in which timber buildings are compared with their mineral and functionally equivalent twins in terms of grey greenhouse gas 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 solid 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 greenhouse gas 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).

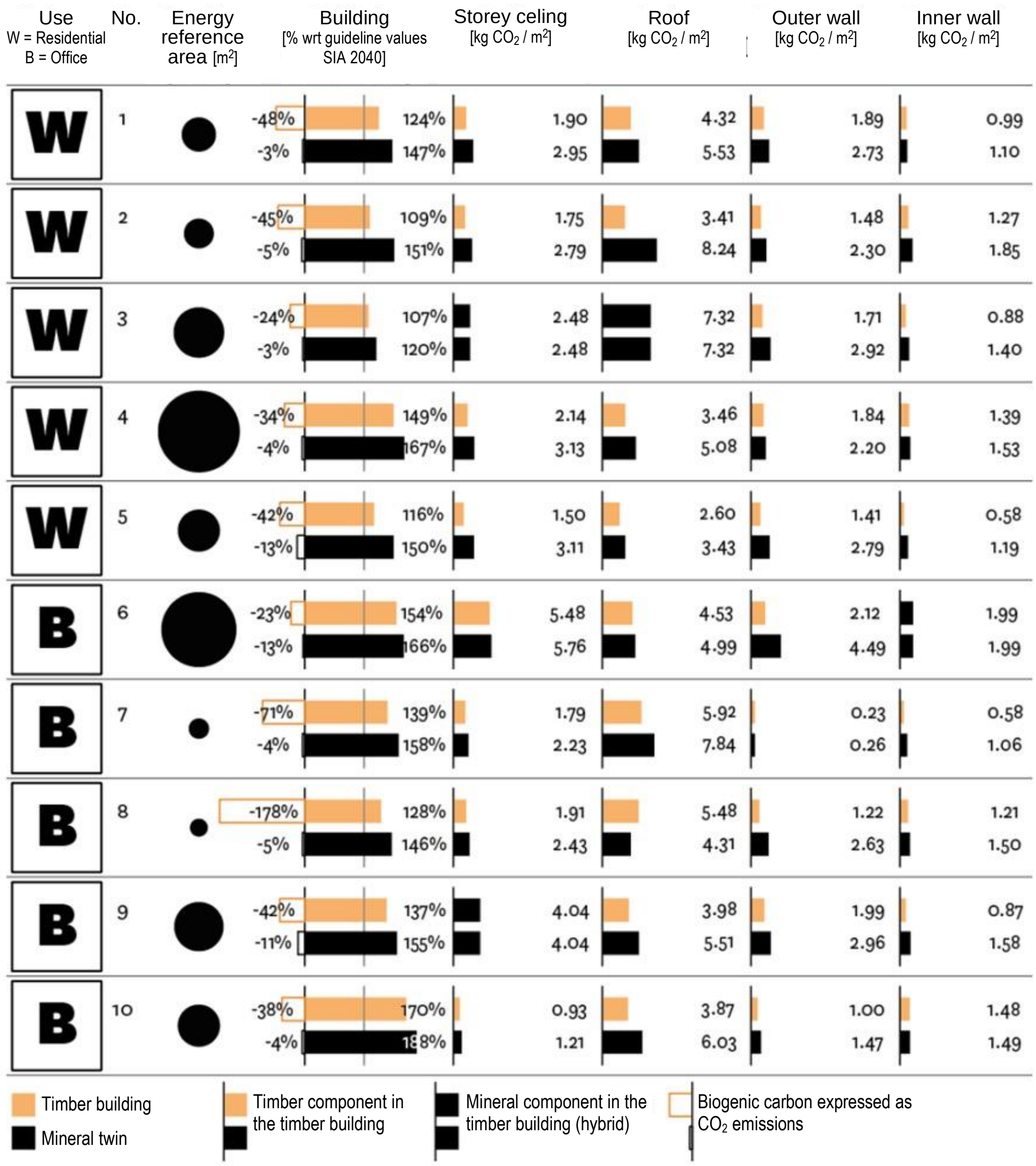

Figure 11: Greenhouse gas emissions from 10 building examples (Lamster 2023, p. 10)

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/m^{2}a).*

*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 greenhouse gas 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 t CO_2eq/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.[21]

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 or natural fibre-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. 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 15).

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

Reduction of destruction of nature

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, 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 forest management therefore also enables an increase in biodiversity.

Avoiding waste and promoting the 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 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 100 years at the end of their life. Wooden beams are already being sold or leased on the

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[21] https://www.bafu.admin.ch/bafu/de/home/themen/klima/zustand/daten/treibhausgasinventar/abfall.html

market with a take-back guarantee and databases are being created with all the wooden construction elements used.[22]

2.3.4 Risks

Permanence

Risks exist in the overexploitation of forests in the case of unsustainable raw material procurement (P. Smith et al. 2019) and with regard to legally ensuring the permanence of carbon in the building or building material at the end of its useful life. In Switzerland, the permanence requirement is 30 years, internationally 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 Pfäffi 2023). Furthermore, there is a risk that, after dismantling the building, construction timber will be utilised for energy production without carbon capture or further utilisation into biochar. This leads to the stored carbon escaping back into the atmosphere. To prevent this risk, Frischknecht and Pfäffli (2023) make two proposals for making permanence legally binding:

- 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 Pfäffi 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 Pfäffi 2023).

Deforestation

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 decarbonisation of the heating industry, and demand will increase as hundreds of new heating networks are planned. The foreseeable shortage of energy wood will lead to price pressure, which will also affect the previous main segment, namely round timber for timber construction. It is questionable whether the construction industry will be able to keep up in terms of price, as heating networks cannot be shut down once they have been built, while alternatives exist in the construction industry. It can therefore be assumed that significantly more logs will be burnt in future instead of being supplied to the construction timber market via sawmills. These negative developments should be prevented by appropriate framework conditions and regulations, as wood in construction has a higher social benefit.

2.3.5 Estimates of costs, potentials, and main drivers

Costs

Several studies analyse timber construction costs and compare the results with solid construction. In most of them, the additional costs are calculated per m^2 of main usable floor area. From the perspective of NETs, it is important to understand the specific costs incurred for CO_2 storage as a result of the increased use of engineered timber construction.

For this purpose, existing cost analyses and internal case studies are analysed and evaluated. However, only the construction costs of the load-bearing structures of buildings are analysed in accordance with

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[22] 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

the building construction cost plan, as the load-bearing structure accounts for around 80% of the total investment volume of residential, industrial, and commercial buildings.

The existing studies show different cost estimates. The study by Selberherr and colleagues (Selberherr et al. 2020) shows median additional costs of around 17% for timber-framed apartment blocks compared to traditional solid construction at the level of the building cost plan. At the extremes, additional timber construction costs of 33% (10%-quantile) and -21% (90%-quantile) are estimated (Selberherr et al. 2020). The final report by Pirmin Jung in 2015, in turn, presents deviating additional cost parameters for the construction costs, which were calculated according to the Swiss Sustainable Building Standard (SNBS). The study shows that multi-family houses (MFH) with a timber construction in the supporting structure are approx. 4.5% more expensive than with a solid construction (Müller et al. 2015).

In other studies, the additional timber construction costs at the level of building costs correspond to approx. 24%. Discussions with investors, project developers and engineers have identified that the different results from the studies are related to experience in the realisation of timber constructions. For this reason, many investors and project developers are of the opinion that timber construction is approx. 15% more expensive than solid construction. Timber construction is more competitive for office buildings than for residential construction (Selberherr et al. 2022).

The results of the internal case studies show the additional costs of the most commonly used timber construction products in load-bearing structures compared to the traditionally used products steel 235 and concrete C25/30. The following timber construction products were compared to the traditional products: Glulam, cross laminated timber, laminated veneer lumber, solid wood (solid timber) and modular construction. The construction methods are compared according to their functional fulfilment. The volume of steel or concrete can be up to 20% less than in timber construction. The costs of the analysis are shown per cubic metre of timber, which means that the additional costs of timber construction can be put directly in relation to CO_2 storage. In general, a median of approx. 14% was calculated, with the additional costs per building element varying between 5% and a maximum of 50%. Figure 12 illustrates the additional timber construction costs at the level of 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 and the smallest cost differences in the ceiling construction.

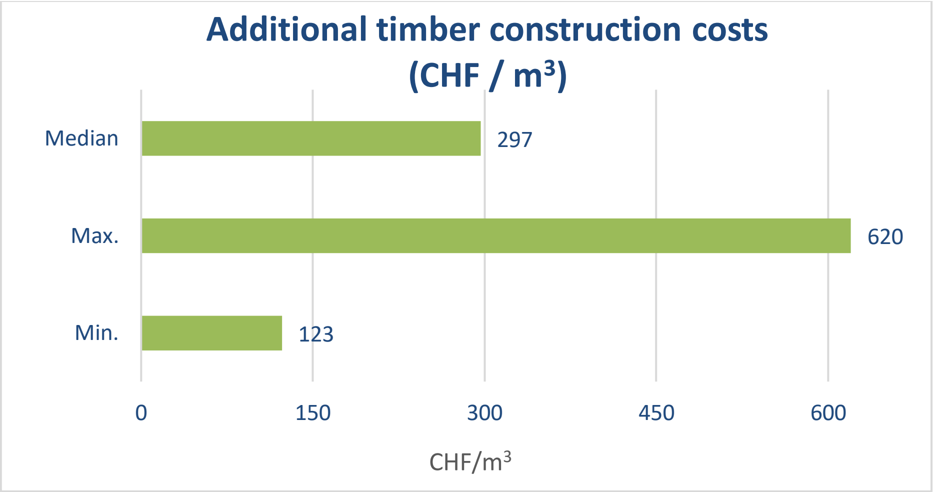

Figure 12: Additional timber construction costs for installed building products in the load-bearing structures compared with the traditionally used and functionally equivalent quantities of solid building products steel 235 and concrete C25/30 (own unpublished calculations, Timber Finance Initiative, 2023).

From the preliminary results of the study research and the case study analysis, it can be shown that the load-bearing structures in timber construction are approx. 10-14% more expensive than in solid construction. The choice of products in the individual element groups has a strong influence on the construction costs.

With the simplified assumption that 1 tCO_2eq is saved per 1 m^3 of wood used, it can be concluded from the internal case study analysis that **1 tCO_2eq saved in construction costs around CHF 300** (see Figure 12). The costs could be further reduced if the avoidance of emissions by substituting concrete and steel were also taken into account. Care must be taken to avoid double counting.

As planners and project developers gain more knowledge, it is expected that the additional costs of timber construction will decrease. As mentioned above, the costs are heavily dependent on experience in the planning and realisation of timber constructions.

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 structure in timber construction, the traditional solid building materials 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%.[23]

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 replacement construction. However, timber construction is one of the most scalable NETs 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 13. The first scenario "CH timber" shows the timber construction potential with the use of exclusively Swiss timber in the supporting structure. The second 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. 208’000 m^3 of glued laminated timber was produced in Switzerland in 2022 (Lädrach 2022).

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 million tCO_2eq per year in construction by prioritising the use of Swiss wood as construction timber.[24] By 2050, a cumulative total of 36.08 million tCO_2eq could be stored with the maximum use of Swiss wood in construction (Bundesamt für Umwelt (BAFU) 2022).

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

[24] 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.

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 million tCO_2eq will be stored in construction over the long term. This corresponds to an annual CO_2 storage of 3.52 million tCO_2eq, meaning that the annual storage can be almost tripled through imports.

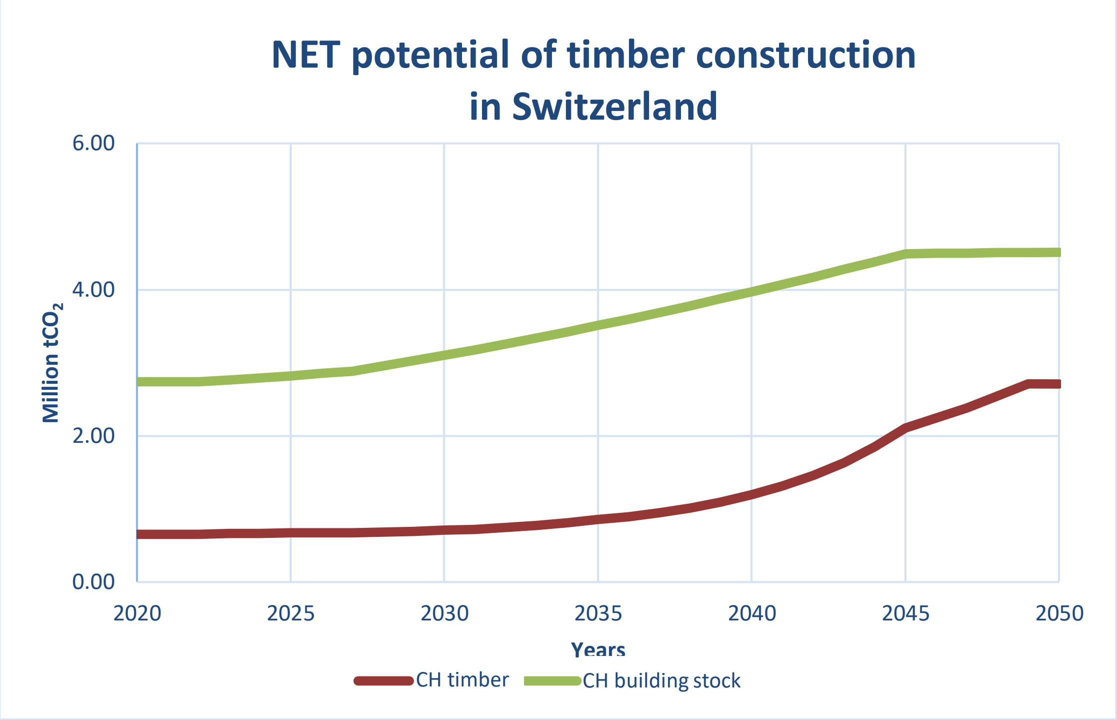

Figure 13: Comparison between the scenarios CH timber in construction (brown) and CH building stock (green). The potential of the building stock corresponds to the maximum use of wood construction in the Swiss construction sector.

The "CH timber" scenario utilises the potential of the Swiss forest by 2050. The scenario can provide the construction sector with approx. 1.2 million tonnes of CO_2eq per 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 (Bundesamt für Umwelt (BAFU) 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 14 shows the cumulative quantity of Swiss and imported wood.

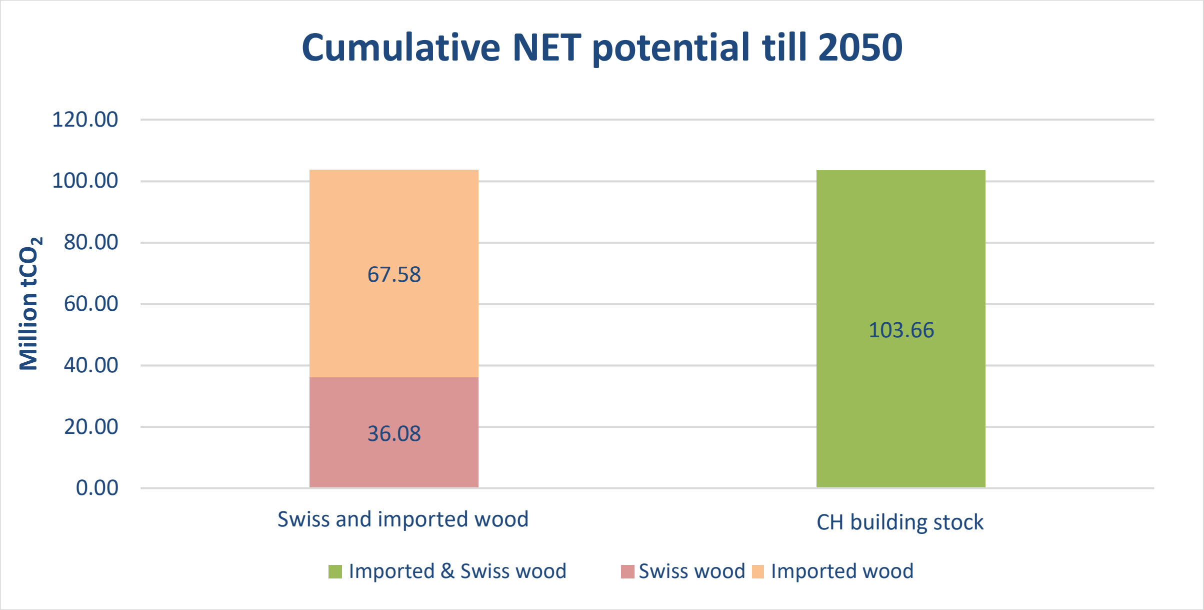

Figure 14: Cumulative potential of the building sector: approx. 65% of the timber required for construction is imported.

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 permanence 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 possible increases through measures in the forest through Climate Smart Forestry (silviculture, tree species, etc.). With this somewhat more complex forest management, the annual growth in wood could be doubled from 8.5 cubic metres/ha to 17 cubic metres per hectare per year. With optimised climate smart forestry, more CO_2 is sequestered in the forest at the same time as wood is produced for construction through faster growth of a rejuvenated, diverse forest. As Figure 15 illustrates, the growth per year and hectare depends on the tree species and tree age. The tree growth per year and hectare is proportional to the sequestration rate. The best CO_2 absorption performance is achieved when the maximum possible sequestration is optimised and at the same time the tree diameter is optimised for the processing industry.

In the context of Swiss greenhouse gas emissions of approx. 46 million tCO_2eq per 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 → 4.7 million m^3/y
Climate Smart Forestry growth:	17 m^3/ha/y → 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.

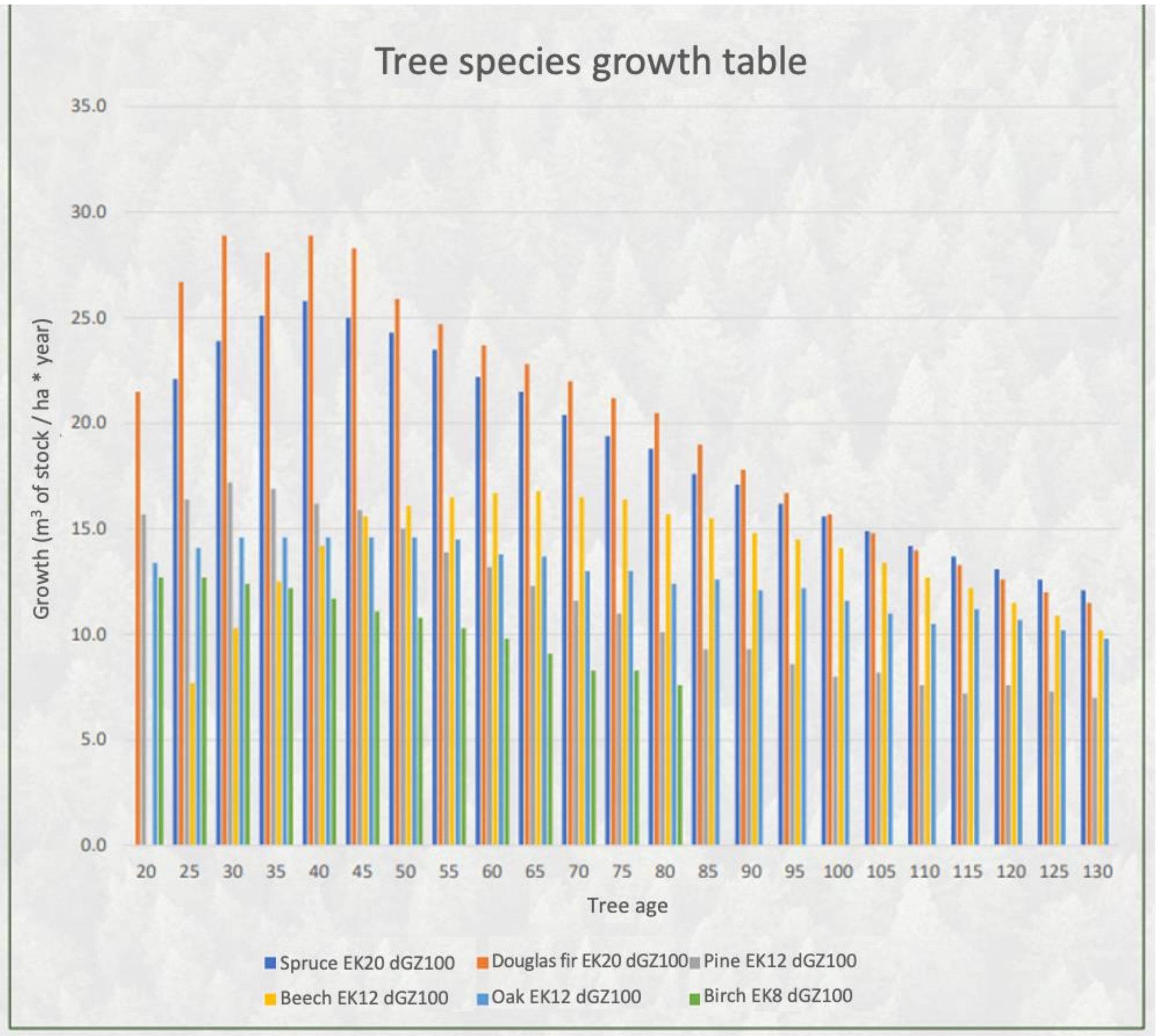

Figure 15: Tree species growth table (Forest Research Centre Freiburg)

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.

2.3.6 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 CO_2 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.[25]
    - **SIA** is the Swiss Society of Engineers and Architects, which, among other things, develops standards in the construction sector and provides them to practitioners. The authors are not aware of any work on TCCS, but the SIA is an important multiplier for any standards relating to permanence and carbon storage in timber buildings.
    - **Verein Senke Schweizer Holz** (Swiss Wood Sink Association), which connects around 150 sawmills and wood-based panel producers who are committed to increasing the use of wood as a CO_2 sink.
    - **Verein Wald-Klimaschutz Schweiz** (Swiss Forest Climate Protection Association) supports CO_2 sink projects in the forest.
    - **Timber Finance Initiative**, which has developed the first standard for monetising CO_2 storage capacity in multi-family houses with the organisation Verra.
    - **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 the Federal Office for the Environment, which are aimed at major investors.
    - **Climate Cent** and **Foundation for Climate Protection and CO_2 Compensation (KliK)**, which play a role in the financing of wood sink projects.

- 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**:
    - 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.

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

2.3.7 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 Objectives, Innovation and Energy Security[26] 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 (Art. 10), and given that the revised Federal Act on Public Procurement as well as the corresponding Ordinance[27] 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[28] 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.

Another approach is the parliamentary initiative to "strengthen the circular economy": the UREK-S (Environment, Spatial Planning and Energy Committee of the Council of States) is expected to deal with this by the end of 2023, with entry into force possible in 2025 at the earliest. The National Council decided on this in May; however, the limit values for grey greenhouse gas emissions in buildings were controversial. It is therefore clear that the issue has reached the political arena.

In 2017 a timber in construction project[29] was carried out within the national research program NFP 66, where some recommendations were made, but there seems to be no resulting policies yet.

Beyond these policy measures and research initiatives, there are some initiatives to support the use of timber in construction as compensation projects both in the compliance and the voluntary carbon markets. Switzerland is the only country in the world that has implemented a programme to remunerate the climate performance of wood in the regulated CO_2 market (KliK, Programme 055)[30], together with the Swiss Wood Sink Association since 2014. This programme, financed by fuel levies, finances uneconomical investments in the second processing stage of sawmills with the aim of compensating them for their climate performance by making the building material more competitive through investments. In this respect, the current programme is not an industry solution but a sector solution and only has an indirect effect on the supply side (forests) or the demand side (investors in timber constructions). The programme no longer meets international requirements and is therefore likely to expire in 2030, as the permanence factor and thus the storage capacity cannot be guaranteed and monetised. In addition to this FOEN programme, there are also several private initiatives on the voluntary market, most of which are not accredited to a high ICROA standard.

Note: The Puro.Earth methodology "Bio-based Construction Materials" has now been discontinued.

Figure 16 shows that these approaches have evolved from a forest focus to an industrial focus to a timber construction focus. This development is probably due to the fact that permanence, 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

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[26] https://www.fedlex.admin.ch/eli/fga/2022/2403/de

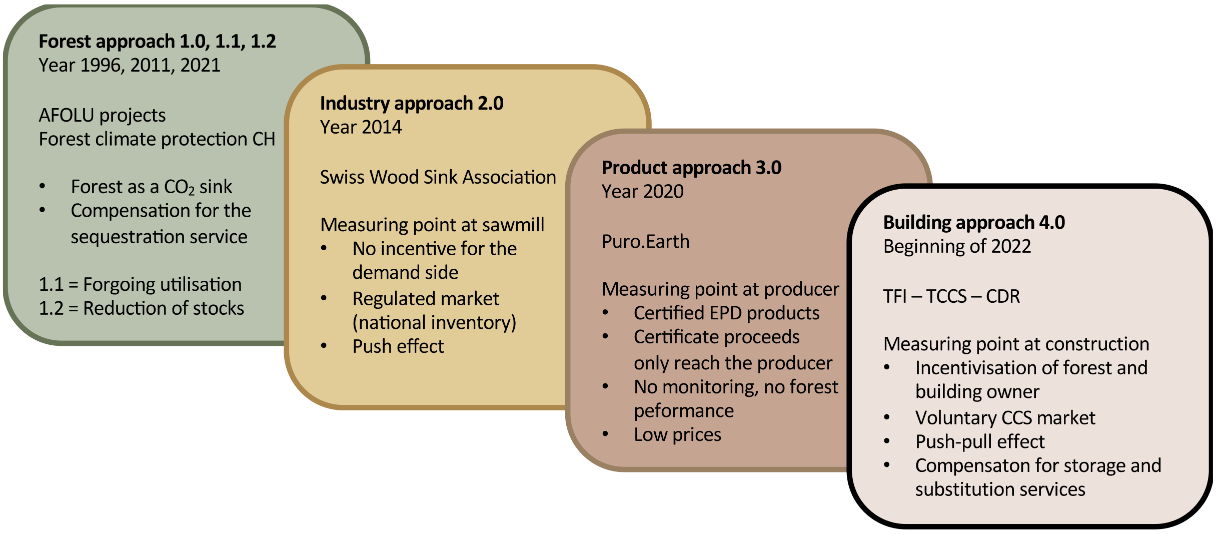
[27] https://www.fedlex.admin.ch/eli/cc/2020/126/de and https://www.fedlex.admin.ch/eli/cc/2020/127/de

[28] https://www.woeb.swiss/de/

[29] https://www.nfp66.ch/de/Ws1uasKdbEmHiIeQ/seite/ergebnisse

[30] https://www.klik.ch/factsheet/index.html?fsid=28&generation=enforce

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.



Note: The Puro.Earth methodology "Bio-based Construction Materials" has now been discontinued.

Figure 16: Development of approaches for the certification and compensation of TCCS (Timber Finance Initiative, 2022).

Internationally

Internationally, various countries and subnational jurisdictions have introduced incentive schemes for buildings that produce fewer emissions, but these schemes do not consider carbon capture (Amiri et al. 2020). Relatively common are governments mandating state agencies to consider and/or to reduce embodied carbon in the materials used for new construction or infrastructure projects. In the US, several states and cities have enacted such regulations, including for example the 2017 Buy Clean California law, the 2020 Los Angeles' Green New Deal, and the 2018 State Efficiency and Environmental Performance executive order in Washington State, among others (Think Wood 2021).

In Europe, the EU Green Deal envisages buildings that align with the circular economy. Timber can help advance such goal. France's Energie Carbone program (now called Energie Positive et Réduction Carbone) established between the government and the construction industry seeks to promote experimentation to achieve positive energy from buildings and lower their carbon emissions throughout their life cycle. To achieve these goals, it offers incentives such as allowing a higher construction density above the zoning limits to buildings that proof certain performance targets, as well as a labelling scheme indicating the performance level of the building in terms of energy efficiency and embodied carbon. More recently, President Macron announced in February 2020 that all new public buildings should use 50% timber or another biomaterial after 2022. The measure was inspired by Paris' mandate to use timber in buildings for the 2024 Olympic games. Belgium has developed its own LCA tool for building materials and now requires manufacturers of construction products to submit environmental product declarations (EPDs) summarizing the results of a LCA. Since 2012, the Netherlands requires all new residential and office buildings above 100 m^2 to report their environmental profile, as well as estimated embodied carbon. Moving from monitoring to regulation, since 2018, in addition, there are thresholds that the estimated environmental profile must not exceed. Sweden's building code includes stringent energy requirements for new buildings and retrofits, with the aim of increasing energy efficiency in buildings by 20% in 2020 and 50% in 2050. From 2022 onwards, in addition, new buildings must report on their climate impact (Think Wood 2021).

In addition, there are voluntary green building certificate schemes, such as the Leadership in Energy and Environmental Design (LEED) Program used widely in the US and the International Green Construction Code (IgCC). According to Amiri et al. (2020), however, these schemes also disregard the potential for capturing carbon, rather focusing on embodied carbon and life cycle emissions.

Also relevant at the harvesting rather than the construction stage are standards for sustainable forest management, such as the Program for Endorsement of Forest Certification (PEFC) and the Forest Stewardship Council (FSC).

Similarly to the case of biochar, a critical challenge for scaling up the use of wood in construction is the lack of standards for its production. As different, non-standardized products are available, engineers and architects need to calculate with the parameters of the specific supplier, making massification of this resource – particularly for structural components – more difficult.[31] Another challenge is that most building codes were adopted before the current high-tech timber construction products were developed, so they need to be updated. Himes and Busby (2020) published a theoretical discussion on policy barriers to the deployment of timber in construction, as well as on suggested policy support options and on mobilising private capital.

2.3.8 Accounting

National GHG inventory accounting

In national GHG inventories, the use of timber in construction represents a form of the category *Harvested Wood Products* (HWP),[32] whereby increases in the carbon sub-pool are reported in the inventory – following IPCC guidelines (2019) (Rüter et al. 2019). 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 is accounting 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 needs 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 the risks section). 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 is more immediately resulting in CO_2-removal. In order for this strategy to be successful the IPCC Default Values will need to be amended.

(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

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[31] https://ec.europa.eu/research-and-innovation/en/horizon-magazine/they-can-capture-more-carbon-they-emit-so-why-arent-wooden-buildings-mainstream

[32] 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).

types. Perhaps the most extreme example of such a change is moving from biomass-energy utilization to utilization of timber in construction.

Accounting in carbon markets

Carbon markets have to date refrained from crediting sector-level changes in stock and HWP-based removals have thus not featured as such in compliance nor voluntary carbon markets to date. To date there have also not been any accepted methodologies for the emissions-reducing effect of utilizing HWP to displace higher-emitting alternatives. To include such project types in carbon markets, baseline- and monitoring, reporting and verification (MRV) methods would need to be developed and accepted 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.

At the individual project level, emissions reductions results from using timber in construction versus using steel or concrete may, however, in the future be credited in voluntary carbon markets: The Verified Carbon Standard (VCS) is presently developing a methodology that allows calculating the emissions-reductions effects from using more timber in construction (versus other construction types that utilize greater amounts of high-emissions steel and concrete). There are, however, numerous challenges also for crediting timber use in carbon markets. These challenges stem from the requirement to demonstrate additionality, permanence, absence of second-order (so-called “leakage”) emissions and the need for transparent monitoring and verification of results.

Much focus is on the need on digital solutions that could lower the transaction costs and the feasibility of proofing additionality. This could be aided through applications that allow the calculation of counterfactual costs in case of a conventional building versus one proposed with greater use of in timber – in order to calculate the additional cost associated with the latter option.

Accounting insights from LCA

Expectations regarding the necessary conditions for monitoring reporting and verification methodologies are evolving with some methodologies in development as mentioned. There is not yet a clear consensus on how to account for Timber Construction Carbon Storage (TCCS) neither at the project level and even the national level of HWP sub-pools is not 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.

In contrast to the case where individual projects are to be accounted for – which requires a cradle-to-grave perspective, when it comes to tracking the results of an accumulation in Harvested Wood Products, a cradle-to-gate approach may be chosen. Therein the emissions from harvest, transport, process, and construction are determined and subtracted from the carbon embodied in the products. The CO_2 content in timber construction is standardized 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 under strict forest laws. Additional possibilities for identifying and managing deforestation risk is through the use of certification schemes such as FSC or PEFC.

When it comes to accounting for individual projects (rather than a sub-sector carbon-pool) the definitions of carbon removal and LCA perspective requires that the permanent storage of CO_2 must be monitored – which means applying a even larger system boundary: cradle-to-grave. Unless the after-use is being monitored and accounted for, carbon storage permanence is not achieved which means that no removal took place. There are ongoing international efforts to account for the NET from timber construction[33] 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.

2.3.9 Open questions

The following open questions must be addressed in the future:

On technological aspects

It is unclear which alternative approaches are adequate for defining the system boundaries for the increased use of wood products and how the system boundaries affect the assessment of such activities in terms of CO_2 removal.

On actors, policies, and accounting

Due to the free choice of accounting rules for HWP among the NDCs under the Paris Agreement, it must be clarified in which cases gaps arise and in which cases double counting is more likely to occur if two countries that trade timber use different methods.

Who owns the achieved sink services of the HWP if compliance markets such as Senke Schweiz and the voluntary market exist side by side?

How can the substitution effects be recognised without leading to double counting?

How can modern accounting rules be drawn up, taking into account the implications of new (standard) developments with regard to reduction projects based on wood products, while ensuring that any increase in demand for wood does not negatively impact ecosystems?

How must additionality be defined, especially in the case of recognising (sub)sector-wide cumulative results instead of individual projects? This requires further analysis of various standards and their regulations and their interpretation in relation to new types of activity.

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[33] See e.g., https://climate.ec.europa.eu/eu-action/sustainable-carbon-cycles/carbon-removal-certification_en

2.4 Bioenergy with Carbon Capture (BECCS)

2.4.1 General description

"Carbon capture" ("CC" in the abbreviation of CCS or of BECCS) refers to various processes for capturing CO_2 from exhaust gases, so-called point sources. If the substrate is biomass, e.g. wood, then it is referred to as "BioEnergy Carbon Capture", i.e., **BECC** (whereby the abbreviation usually includes the S for storage, i.e. BECCS). 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, 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). 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 rocks, 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: 1) Methods that fix the carbon for a long time, for example in aquifers, rocks or former oil and gas deposits, as well as carbonation of concrete granulate; 2) 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" (**U**). This results in a total of four combinations and the corresponding abbreviations, of which only the sequestration of biogenic carbon can be considered a negative emission (**BECCS**). The (re)use of fossil or geogenic carbon as a substitute for fossil fuels in applications that are difficult to decarbonise, for example, increases the CO_2 concentration in the atmosphere (**CCU**) and can only be seen as a transitional solution at best. **CCS** 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, **BECCU** will have to be used to produce everything that is currently obtained from fossil raw materials. 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, diesel, paraffin) or chemical precursors (primarily methanol and other alcohols and ethers) and thus replace fossil products.

Origin of carbon **Use of carbon**	**fossil, geogenic (coal, crude oil, natural gas, rocks)**	**biogenic (biomass)**
S – Sequestration, e.g., fixation in rocks, deposits, permanent components	**CCS** Significant reduction in emissions	**BECCS** Negative emissions, thus reducing greenhouse gases in the atmosphere
U – Utilisation for energy sources, chemicals, consumption goods	**CCU** Minor reduction in emissions	**BECCU** Significant reduction in emissions, climate-neutral in the long term

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

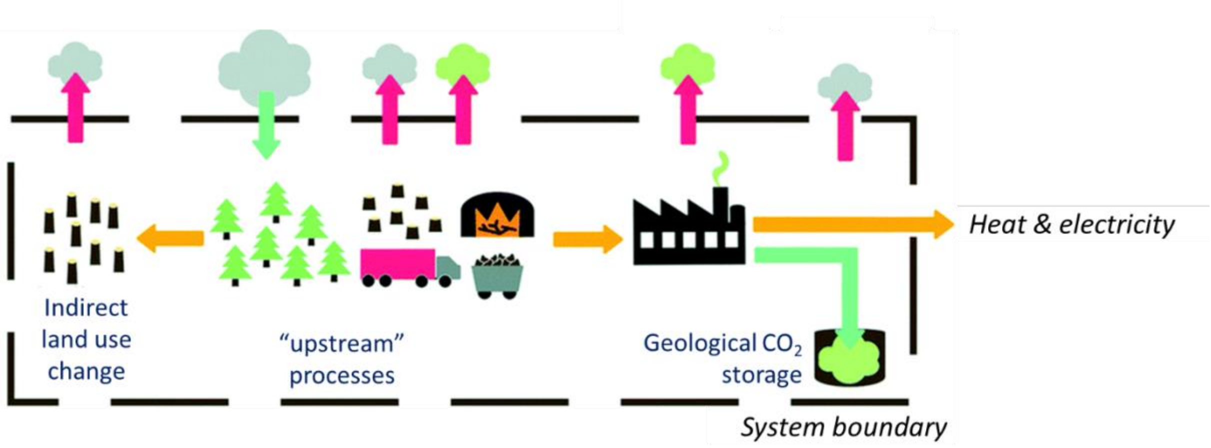


Figure 17: System boundaries of a BECCS system for heat and electricity generation.

The following processes and associated carbon fluxes must be taken into account when balancing climate impacts: 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.

As the term "(bioenergy with) carbon capture and storage" ((BE)CCS) includes numerous technology options, system boundaries for accounting the climate impacts and other environmental burdens can hardly be formulated in a way fitting to all these options (Fajardy and Dowell 2017; Kemper 2015; Withey et al. 2019). In the most generic way, BECCS includes the following processes: a) Removing CO_2 from the atmosphere by growth of biomass, b) converting biomass into products used as energy carriers or secondary biogenic feedstock, c) CO_2 capture, d) CO_2 transport and e) finally permanent CO_2 storage. Carbon Dioxide Removal (CDR) as a service therefore includes the following key processes of the BECCS product system, the entire biomass supply chain (growth, harvesting, transport), its conversion to secondary products, and carbon capture, transport, and storage processes (see subsequent sections on transport and storage).

BECCS systems typically represent multi-output systems 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 and heat. 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: Wood combustion, Waste-to-Energy (WtE) plants, wastewater treatment plants (WWTP), 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 addition to CDR, wood combustion, WtE and WWT plants with CCS generate 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 heat, electricity and cement would replace marginal production of heat, electricity and cement, 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.

If wood is not used in higher quantities than the rate of natural growth in forests, 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. Such system-wide analysis will be performed within the remaining project period.

2.4.3 Co-benefits

Climate-relevant co-benefits

- Exploiting synergies with other plants saves costs and energy and therefore greenhouse gases: 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.

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 fossil carbon as a raw material for industry, making it more flexible and less dependent on carbon imports.

2.4.4 Risks

Climate-relevant risks

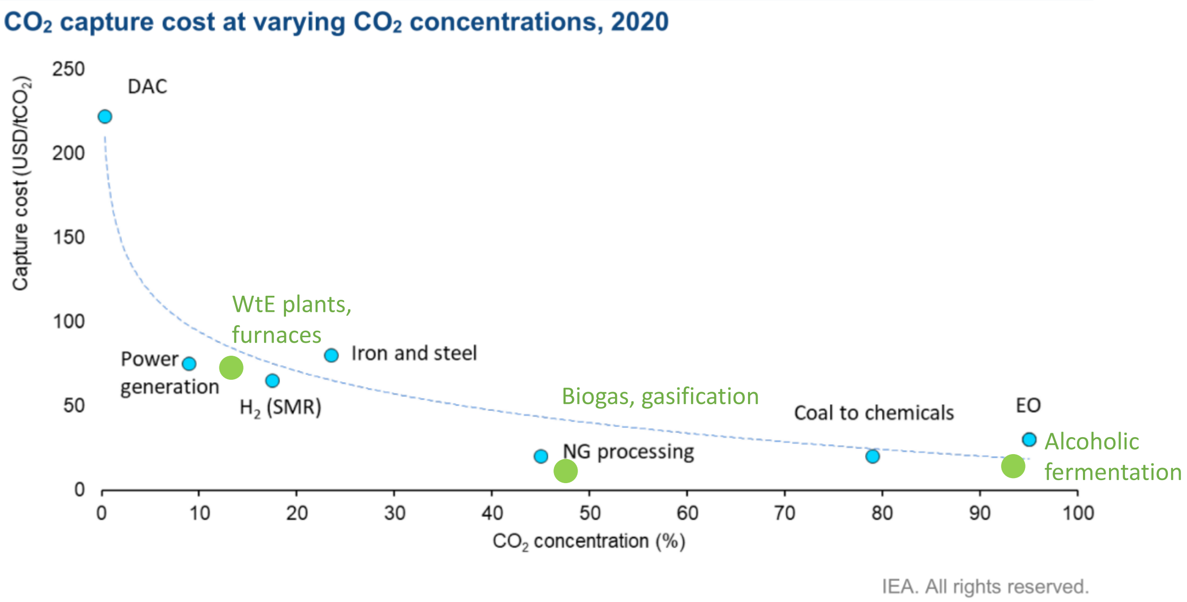
- Environmental pollution due to chemical additives (e.g., amines) and the loss of greenhouse gases into the atmosphere (e.g., methane slip).
- Unclear allocation of negative emissions can lead to greenwashing. Transparency and control are necessary to avoid double accounting.
- The injection of CO_2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

Other risks

- Depending on the procedure, the operating licence and insurance requirements are unclear.

2.4.5 Estimates of costs, potentials, and main drivers

The costs of carbon capture from various industrial processes were analysed in a study by the IEA (International Energy Agency 2022) and are shown in Figure 18. 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 a main co-product, e.g. gasification or fermentation, therefore have the lowest CO_2 supply costs. Typical CO_2 contents of gases from industrial processes used in Switzerland are listed in Table 3. The other components such as oxygen or methane content have an influence on which capture technologies can be used.



Notes: Average values by application. H_2 = hydrogen; SMR = steam methane reforming; NG = natural gas; EO = ethylene oxide. The empirical trend line shows the correlation between capture cost and CO_2 concentration.

Figure 18: Costs of carbon capture from various industrial processes (International Energy Agency 2022, p. 27). Biomass-based processes were added by the authors.

Table 3: 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 4 lists processes for the separation of CO_2 from industrial gas mixtures, whereby a distinction is made between different modes of action. 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 countercurrent (see Figure 19), 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 but requires a higher energy input (usually higher temperatures >160°C) for the regeneration of the scrubbing agent.

Table 4: 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. Brugg, Turgi, Wildegg WWTPs	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)			

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 boilers in the different phases of adsorption and regeneration are usually applied in order to achieve continuous CO_2 separation.

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, albeit 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 CO2 separation process must be made individually 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.

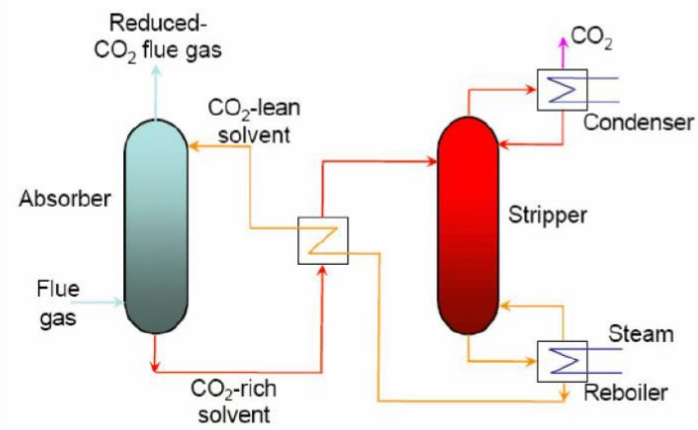


Figure 19: Schematic sketch of a CO_2 scrubber (e.g., amine scrubber)

Potential for point sources in Switzerland

Some time ago, 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 20), 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 proportion 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 and 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 is captured again when the products from the PtX are utilised, the potential increases again.

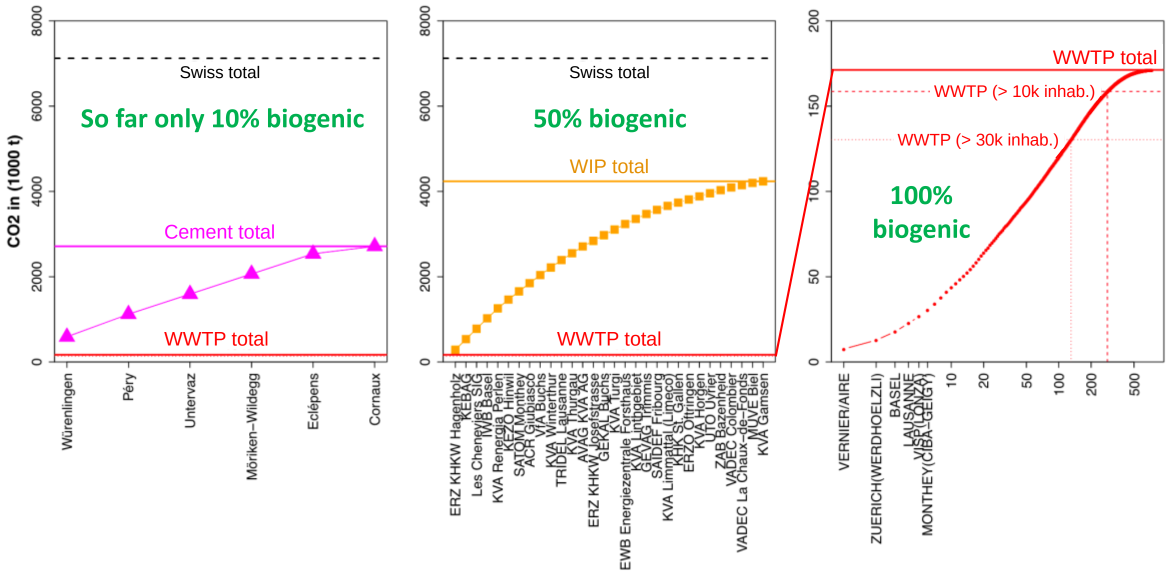


Figure 20: CO_2 point sources in Switzerland: cement plants, waste incineration plants (WIP) and wastewater treatment plants (WWTP); cumulative presentation of annual CO_2 emissions, sorted by decreasing contribution of the plants in each (Teske et al. 2019).

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 21.

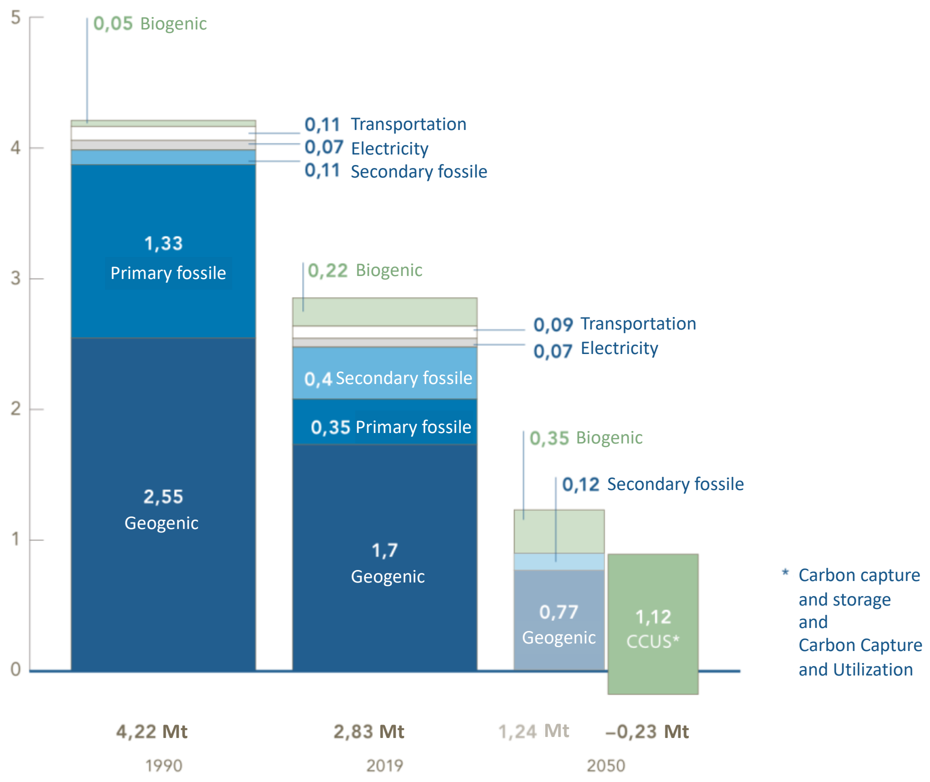


Figure 21: Emissions from the Swiss cement industry in 1990, 2019 und 2050 (Cemsuisse 2021)

Note: It can be seen that about 1/3 of fossil fuels have already been saved. Further savings are planned by 2050.

2.4.6 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[34] together with the ETH and the VBSA[35], 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[36], one of the DeCIRRA implementation partners and actively involved in the decarbonisation debate.

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[34] https://www.kva-linth.ch/energie-umwelt#section-id-100
[35] https://vbsa.ch/
[36] 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 greenhouse gas emissions and promote sustainable technologies.

As mentioned above, the two most important associations are CemSuisse and the VBSA. However, Holzenergie Schweiz (Swiss Wood Energy)[37] 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[38] operates the Swiss Carbon Removal Platform[39], informs and brings together the industry, and organises events and meetings on a regular basis. It is also involved in many projects, including DeCIRRA.

2.4.7 National and international policies and incentives

To assess the policy framework for BECC different frameworks need to be considered depending on the different contexts in which BECC 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 60 million CHF from the Climate Cent Foundation[40] for NET and CCUS

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[37] https://www.holzenergie.ch/
[38] https://www.risiko-dialog.ch/
[39] https://www.carbon-removal.ch/
[40] https://www.klimarappen.ch/en/Negative-emissions-technologies.1.html

projects, as well as (iii) the agreement[41] between the Swiss government and the Swiss association of waste-to-energy plant operators (VBSA). Under this agreement, 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, finalizing the construction project, etc. If the goal is nonetheless not achieved, the waste-to-energy plants will have to participate in the Swiss ETS.[42]

Article 6 of the recently adopted Climate and Innovation Act (Schweizerische Eidgenossenschaft 2022) has introduced new funding of 1.2 billion francs to support industrial and commercial companies that use innovative climate-friendly technologies to meet (part of) their net-zero emissions plans. While details on the requirements for accessing this finance still need to be regulated by the Federal Council, it is expected that CCUS technologies – including BECCS – will be included.

BECCS in cement plants are currently covered under the Swiss ETS which so far does not include the possibility to issue removal units (see further discussion on BECCS and ETS below). Wood energy plants are exempted from the Swiss ETS.

Internationally

According to the IEA Policies database[43], several countries, including Australia, Canada, Denmark, the EU, Finland, Germany, the Netherlands, Norway, Sweden, the UK and the US, have introduced schemes to financially support investments in CCUS technologies, commonly as part of post-Covid recovery packages. Some of these schemes, particularly the one from the EU, are partly financed from the revenues obtained from the auctioning of allowances under the EU ETS. Of these schemes, only the Danish NECCS Fund targets specifically biogenic CO_2 sources.

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, such tax credits are established on a percentage basis, with the rates decreasing after 2031 to encourage rapid adoption. In the US, the Section 45Q tax credit established specific amounts per tonne of CO_2 permanently stored. Higher rates are granted for DACS than for all other CCUS technologies. While in Canada Enhanced Oil Recovery (EOR) projects are not eligible for the tax credit, in the US those receive a lower rate.

In addition, Sweden has announced a reverse auction scheme to specifically support investments in bio-CCS facilities, with the aim of promoting this technology while encouraging low costs. While the first auction is planned to take place in 2023, the first payment will likely be disbursed by 2026, after both the project and the storage have been organised.

BECCS installations currently do not fall within the scope of the EU ETS, but there are ideas on how the EU ETS could be amended for this purpose. Under the EU ETS, the supply of emissions allowances will likely need to reach zero or even negative numbers before 2050 so that the EU can meet its net-zero GHG emissions goal. Under these circumstances, the continuation of the EU ETS can only be possible if credits for CO_2 removals are introduced. However, traditional cap-and-trade systems do not consider this possibility, because they are based on the premise that there are installations which generate emissions for which allowances need to be surrendered. While the current version of the ETS Directive establishes incentives for CCS by stipulating that allowances do not need to be surrendered for emissions that have been captured and transferred to an authorized storage site (Article 12(3a)), this

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[41] https://www.bafu.admin.ch/bafu/de/home/themen/klima/fachinformationen/verminderungsmassnahmen/branchenvereinbarungen/vereinbarung-kehrichtverwertungsanlagen.html

[42] 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.

[43] https://www.iea.org/policies

incentive is limited to fossil fuel-based installations. For these reasons, the ETS does not yet provide a legal basis for generating CO_2 removal credits (Rickels et al. 2020).

There are several proposals on how the EU ETS could be amended so that removal credits can be incorporated (Rickels et al. 2020). One option could be to integrate removal credits in a similar way to how the Kyoto Protocol's flexible mechanisms were integrated, using quantity and sectoral limitations to avoid diluting the incentive for actual emission reductions. However, as long as negative emission technologies remain uncompetitive against conventional abatement technologies, such system would not be sufficient to incentivize their uptake. In such a case, obligations to use a minimum quantity of removal credits would be a better option to promote their development. Another option would imply allowing biomass-burning installations into the ETS. However, because upstream emissions and removals from biomass production are currently accounted for under the LULUCF regulation, this could lead to double counting of these upstream emissions both under the LULUCF regulation and again under the EU ETS. This problem could be circumvented by allocating free allowances to biomass installations, which they could sell once they have captured and stored their biogenic CO_2 (Rickels et al. 2020).

According to cdr.fyi, some BECCS removals have been traded in the voluntary carbon market, but none of the projects listed so far have delivered any units yet.

2.4.8 Accounting rules

GHG Inventory accounting

The IPCC Guidelines for national inventories provide clear guidance regarding the accounting of results from capture and (underground) storage of CO_2 from point sources. This guidance pertains to all activities which involve underground storage of CO_2 (CCS) – independently of the source of the carbon (biogenic or not): in the greenhouse gas inventory sector in which CO_2 was captured, the volume of CO_2 that was captured in any given year is subtracted. The CO_2 stored is indicated as a memo item in the energy sector of the country in which it was stored – this, however, does not affect the emission figure. However, there is ambiguity in cases of international displacement of CO_2 for CO_2 capture: In one interpretation, the resulting CO_2 removal should be counted in the greenhouse gas 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). Should there be any leakage during transport or storage of the CO_2, the amount of CO_2 emitted as a result is to be declared in the *energy* sector of the country in which the leakage physically took place (Eggelston et al. 2006, Chapter 5, Section 5.10).

Baseline- and monitoring reporting and verification

Though formally eligible under the clean development mechanism, CCS-based projects have not really entered mainstream baseline- and credit carbon markets to date. However, both the American Carbon Registry (ACR) and Verra's Verified Carbon Standard (VCS) are adopting relevant MRV methodologies, which – going forward – permit the crediting of emissions reductions or carbon dioxide removals from CCS activities and to reap revenue from sales on the voluntary carbon markets. Furthermore, CCS-based activities are in principle also eligible to participate in the emerging Paris Agreement compliance market (Art. 6) as soon as methodologies will be adopted after its supervisory body has fully developed the requirements for such methodologies.

2.4.9 Open questions

The following open questions must be addressed in the future:

On risks, benefits, costs, potentials and their drivers:

- Should wood no longer be burned at all, but only pyrolysed, hydrothermally carbonised or gasified? So where does BECCS compete with biochar and where are the optimum utilisation ratios?
- What scenarios do we need, how are these created and selected in order to achieve the most sensible overall energy system possible?
- 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 best) 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?
- Who bears the operating costs, e.g. of CCS in a waste incineration plant? Does the polluter-pays principle require an increase in the charge on the waste bag or how can capture be financed? What alternative financing models are there?

On actors, policies and accounting:

- How can the legislator ensure that climate-damaging systems, e.g. in district heating, are no longer worthwhile and that they switch to alternative, climate-neutral systems?

2.5 Direct Air Capture (DAC)

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 is a technology that overcomes the spatial and arable land limitations associated with large-scale afforestation and BECCS. DAC offers significant flexibility in siting, allowing it to be placed in any area with low-carbon energy and access to CO_2 storage or utilization opportunities. It can also be positioned near existing or planned CO_2 transport and storage infrastructure. DAC plants have been successfully operated in various climates in Europe and North America, additional testing is ongoing in locations with extreme climate conditions such as dryness and high humidity.

DAC can be classified into two main types: Low temperature solid (S-DAC) and high temperature liquid sorbent (L-DAC) based technologies (see Figure 22), which differ in the methods they use to capture carbon dioxide (McQueen et al. 2020). In the case of **solid sorbent DAC**, the process is conducted in batches, involving distinct adsorption and regeneration stages that utilize temperature or temperature and vacuum fluctuations at around 100°C for the latter. Adsorption onto the solid sorbent can be achieved through weak intermolecular forces, physisorption or chemisorption, often employing amine type groups on highly porous, large surface materials. Subsequently, the regeneration step releases the concentrated CO_2 for storage.

Liquid DAC (L-DAC) operates using a dual closed-loop system. The initial loop occurs within a device known as the contactor, where atmospheric air is exposed to an alkaline solution (such as potassium hydroxide to form K_2CO_3) to capture CO_2. In the subsequent loop, the captured CO_2 is released from the solution through a sequence of units (ion exchange of potash K_2CO_3 with calcium hydroxide $Ca(OH)_2$, subsequent calcination of $CaCO_3$ at approximately 900 °C, followed by forming $Ca(OH)_2$ from the calcination product CaO). The energy-intensive nature of L-DAC, primarily due to its high-temperature demands, has historically posed a challenge for its widespread adoption.

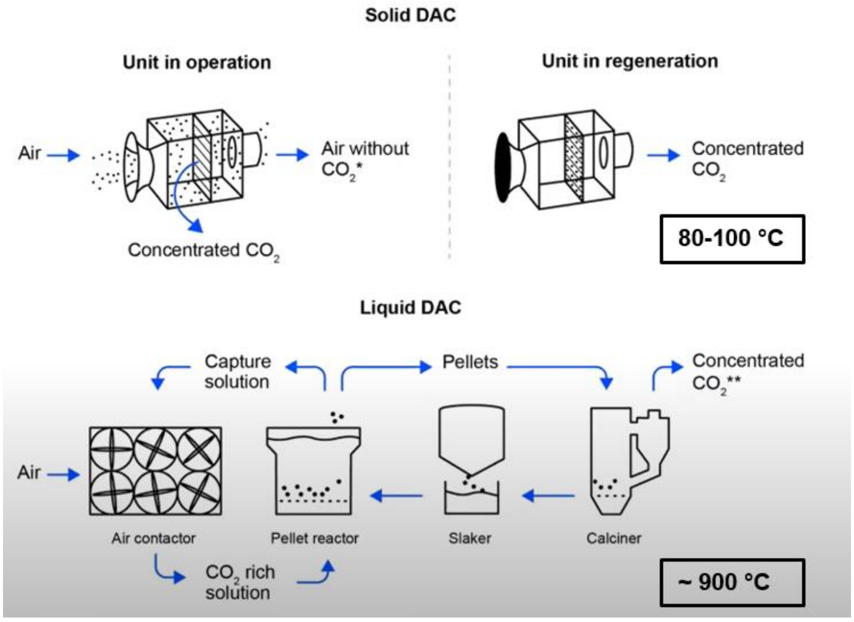

Figure 22: S-DAC (top) and L-DAC (bottom) configurations (International Energy Agency 2022, p. 22).

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 CO_2 transport and injection (Figure 23). Furthermore, negligible leaking of CO_2 from the geological reservoir has to be ensured via long-term monitoring.

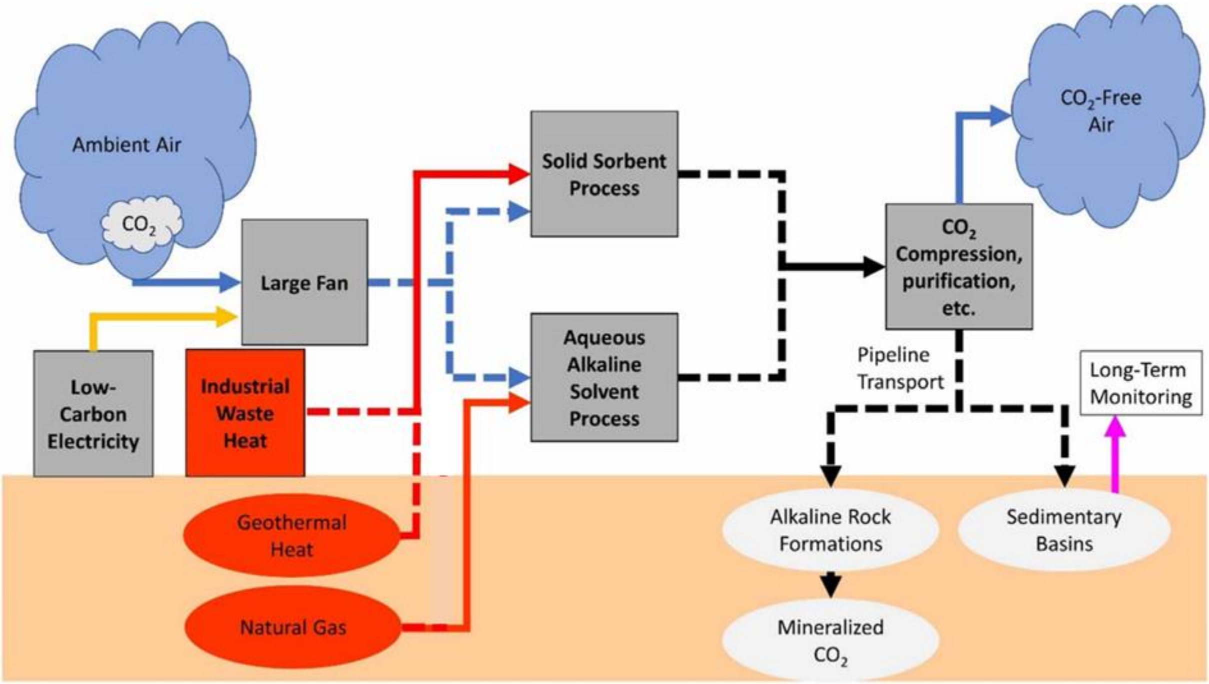

Figure 23: Schematic process diagram of DACCS systems (adapted from Sovacool et al. 2022).

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 greenhouse gas 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 Utilization (CCU)**: Captured CO_2 can be utilized in various ways, such as in the production of synthetic fuels, chemicals, or building materials, providing opportunities for carbon utilization and reducing the reliance on fossil fuels.
- **Renewable energy integration**: DAC plants have to be powered by renewable energy sources, facilitating the integration of clean energy technologies and helping to achieve decarbonization 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 Potentials

The number of operating DAC facilities worldwide has increased in recent years. These facilities are currently small scale, collectively capable of capturing nearly 0.01 $MtCO_2$ per year. However, there is progress in developing a large-scale DAC plant with a capacity of 1 $MtCO_2$ per year. To achieve net zero emissions, a substantial increase in DAC deployment is required during this decade. In the IEA Net Zero Emissions by 2050 Scenario, DAC deployment rapidly expands, reaching approximately 85 $MtCO_2$ in 2030, 620 $MtCO_2$ in 2040 and 980 $MtCO_2$ in 2050 (International Energy Agency 2022).

Between 2020 and 2050, approximately 12 $GtCO_2$ are expected to be cumulatively captured through DAC. It accounts for around 13% of all CO_2 emissions captured, with 64% of this captured CO_2 being stored. This significant DAC contribution, in conjunction with BECCS, helps balance and offset all remaining emissions from the transportation, industrial, and building sectors, thereby enabling the attainment of a net-zero emissions energy system (International Energy Agency 2022).

In 2050, according to IEA's Net Zero Emissions by 2050 Scenario, approximately 350 $MtCO_2$, representing 36% of the CO_2 directly captured from the atmosphere, is utilized alongside hydrogen to produce synthetic hydrocarbon fuels. These fuels are primarily intended for aviation, where they fulfil around one-third of the industry's fuel demand. The use of air-captured CO_2 allows these synthetic fuels to be climate-neutral throughout their life cycle, considering that the CO_2 released during combustion will be offset by the initial capture. This highlights the significance of DAC as one of the limited solutions available to mitigate emissions in the challenging aviation sector, which remains one of the most difficult areas to decarbonize.

In a study conducted by Shayegh et al. (2021), 18 experts from various industries and academia were interviewed regarding negative emissions and direct air capture (DAC) technologies, as well as the economic and policy aspects related to them. 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 emphasized 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 support 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 24 illustrates the ranking of these limiting factors.

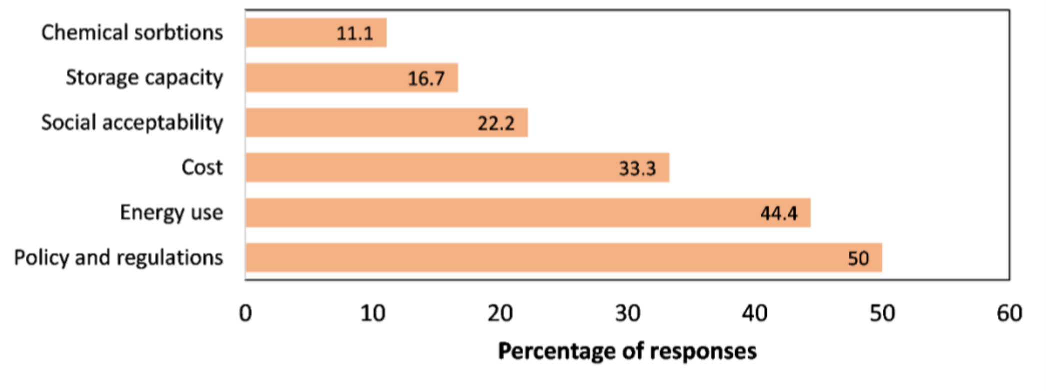

Figure 24: Experts' responses on the DAC development limiting factors (adapted from Shayegh et al. 2021).

2.5.6 Estimates of costs and main drivers

As previously mentioned, DAC systems require a significant amount of energy to operate and therefore need a reliable and renewable energy source. A range of renewable energy sources are available in Switzerland, including hydroelectric power, solar power, wind power, and geothermal energy for heating. While hydropower is currently the dominant energy source in the country, there is limited room for expansion. Additionally, wind power faces challenges due to lower wind speeds than at coasts, natural landscape preservation efforts, and so far, low public acceptance. However, solar photovoltaics have the potential for further development, even at low irradiation levels. This report focuses on exploring the feasibility and cost-effectiveness of integrating PV and wind power as the primary electricity source for DAC systems. Heat pumps, which run on renewable electricity, can also be employed to provide heat for these systems.

The calculation of the levelized cost of electricity (LCOE) and levelized cost of heat (LCOH) provide an essential tool for assessing the cost-effectiveness of different electricity sources over the entire lifetime of a power plant. The LCOE and LCOH calculations for PV, wind and heat pump are based on various factors, including the initial capital cost of the system, ongoing maintenance and operating expenses, the projected lifespan of the system, and the estimated amount of electricity (or heat) that the system will produce over its lifetime. Additionally, the calculation considers the cost of financing the system, including the interest rates and duration of the loan. The LCOE and LCOH calculations are important metrics for investors and policymakers, providing a comprehensive analysis of the long-term financial viability of a project. A low LCOE is indicative of a more cost-effective and competitive source of electricity, thus making it a valuable tool for decision-making regarding the implementation of renewable energy projects.

The equations below have been used to calculate the levelized cost of electricity (LCOE) and the levelized cost of heat (LCOH) (Fasihi et al. 2019).

$$LCOE = \frac{Capex\,.crf + Opex_{fix}}{FLh} + Opex_{var} + \frac{fuel}{\eta}$$

$$LCOH = \frac{Capex\,.crf + Opex_{fix}}{FLh} + Opex_{var} + \frac{fuel}{\eta} + \frac{LCOE}{COP}$$

$$crf = \frac{WACC\,.(1+WACC)^{N}}{(1+WACC)^{N} - 1}$$

Whereas:

- Capex = capital expenditures,
- crf = annuity factor,

- Opex = annual operational expenditures,
- fix = fixed,
- var = variable,
- FLh = full load hours per year,
- fuel = fuel costs,
- η = efficiency,
- COP = coefficient of performance of heat pumps,
- WACC = weighted average cost of capital,
- N = lifetime.

Cost data: The cost information for the three technologies (PV, wind and heat pumps) are taken from the Swiss TIMES Energy Systems Model (STEM) (Kannan and Turton 2014).

PV profile Switzerland: Notable examples of Swiss cantons that experience relatively sunnier conditions include Valais, Ticino, and Basel. To determine the solar potential of these locations, the PV profiles were obtained from the *Renewables.ninja* website.[44] Based on the available data from 2019, it was found that Valais had a high FLh value of 1550 hours, indicating a significant amount of solar energy generation. Ticino, another sun-drenched region, exhibited a FLh of 1400 hours, while Basel recorded a respectable FLh of 1281 hours. These figures highlight the solar productivity of these cantons, making them favourable areas for harnessing solar energy.

Over the past years, alpine solar plants[45] have garnered significant interest for their remarkable power generation potential, particularly during the winter months. A case is the dam in the Glarus Alps, situated at an elevation of 2500 meters, which houses a 2.2 MW PV installation, constructed by Axpo and IWB. Data collected from this site revealed an impressive FLh value of 1500 (see Figure 25).

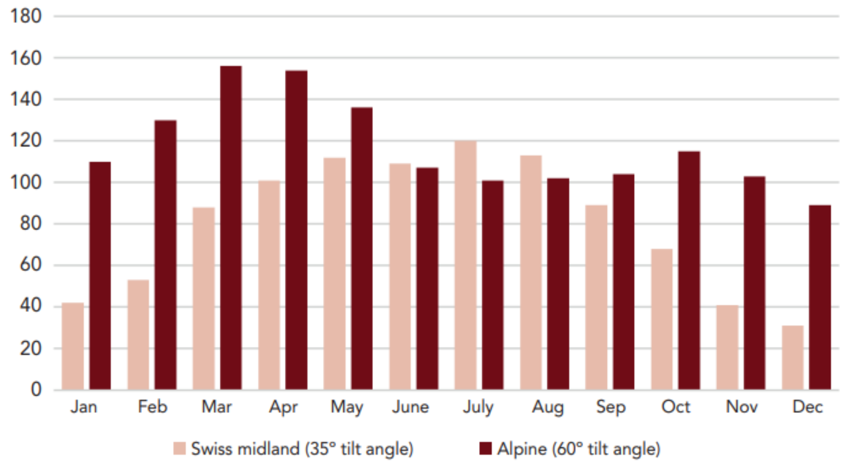

Figure 25: Annual production profile of alpine solar vs Midlands. Alpine solar plants generate significantly higher power in winter months compared to the Midlands plants.[46]

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[44] https://www.renewables.ninja

[45] https://www.alpinsolar.ch/ch/de/home.html

[46] https://www.axpo.com/ch/en/about-us/energy-knowledge.detail.html/energy-knowledge/pioneer-project-in-the-swiss-alps.html

Table 5: Estimation of LCOE by non-alpine PV in Switzerland, current and in the future. Cost-specific information are taken from Kannan and Turton (2014).

		2020	**2030**	**2040**	**2050**
Capex	CHF/ kW_e	900	500	400	400
Opex fix	% of Capex p.a.	1.5	1.5	1.5	1.5
Opex var.	CHF/kWh_{el}	0	0	0	0
lifetime	year	20	30	35	40
WACC	%	5	5	5	5
FLh	h	1400	1400	1400	1400
$LCOE_{PV}$	**CHF/ MWh_{el}**	**62**	**34**	**28**	**27**

Wind power: The LCOE of wind power is primarily influenced by two factors: the specific wind conditions at a location and the level of technological maturity utilized to harness those conditions. Consequently, the LCOE can vary significantly between different countries or locations. Ongoing advancements in wind turbine technology are currently concentrated on achieving higher energy production, primarily by increasing tower heights or enlarging rotor sweep. However, the increased use of materials must be offset by a substantial increase in full load hours to ensure that the higher investment costs are economically viable. These improvements are particularly expected to benefit the deployment of low-wind turbines.

We have utilized publicly available data from the SFOE[47] to gather information about the wind conditions and the number of hours wind turbines operate at full load in Switzerland. The SFOE provides data on the operational wind turbines in the country, offering insights into their types and the electricity they generate. Full load hours (FLh) are determined by considering the size of the wind turbine and its annual electricity production.

Table 6: Full load hours information of wind turbines installed in Switzerland from 2018 to 2022.

year	Martigny VS	Peuchapatte JU	St. Brais JU	Haldenstein GR
	2MW Enercon, 100 m	3* 2.3 MW Enercon, 108 m	2* 2 MW Enercon, 78 m	3 MW Vestas, 119 m
2018	2233	1808	1703	1640
2019	2226	2217	2098	1543
2020	2272	2246	2006	1513
2021	2220	2077	1971	1459
2022	2236	2125	1975	1488
Avg. FLh	**2237**	**2094**	**1950**	**1529**

Table 7: Estimation of LCOE by wind turbine in Switzerland, current and in the future. Cost-specific information are taken from STEM data base (Panos et al. 2022, 2023).

		2020	**2030**	**2040**	**2050**
Capex	CHF/ kW_e	2300	2200	2100	2000
Opex fix	% of Capex p.a.	2	2	2	2
Opex var	CHF/kWh_{el}	0	0	0	0
lifetime	year	25	25	25	25
WACC	%	5	5	5	5
FLh	h	2200	2200	2200	2200
$LCOE_{wind}$	**CHF/ MWh_{el}**	**81**	**77**	**74**	**71**

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[47] https://opendata.swiss/en/dataset/windenergieanlagen

Heat pump: Electrical compression heat pumps have been used for heat generation. The cost specific data are taken from the STEM database. The LCOH are calculated for the operation of heat pump based on both wind and PV, i.e. the same FLh for the heat pump is considered.

Table 8: LCOH for electrical compression heat pump. COP data are taken from Fasihi et al. (2019).

		2020	**2030**	**2040**	**2050**
Capex	CHF/ kW_e	360	360	360	360
Opex fix	% of Capex p.a.	1	1	1	1
Opex var	CHF/kWh_{th}	0	0	0	0
lifetime	year	25	25	25	25
WACC	%	5	5	5	5
COP	-	3	3.26	3.41	3.51
$LCOH_{heat\ pump}$ (based on $LCOE_{wind}$)	**CHF/ MWh_{th}**	**40**	**36**	**34**	**32**
$LCOH_{heat\ pump}$ (based on $LCOE_{PV}$)	**CHF/ MWh_{th}**	**49**	**39**	**36**	**35**

Levelized Cost Of DAC (LCOD)— The following equation is used to calculate the LCOD:

$$LCOD = \frac{Capex_{\ DAC}.crf + \ Opex_{fix}}{Output_{CO2}} + LCOE.DAC_{el,input} + LCOH.DAC_{th,input}$$

Fasihi et al. (2019) conducted a literature review on DAC and observed significant variations in the reported or estimated energy consumption and costs associated with this technology. Recognizing the high level of uncertainty and disparate data in the literature regarding the techno-economic aspects of DAC technologies up to the year 2050, three parameter sets are used for the analysis in this report: DAC system cost, energy demand, and lifetime. Results are shown in Table 9. The breakdown of costs for the LCOD reveals that in 2020, a significant portion of the total investment cost, specifically 84%, was allocated to the DAC system, Figure 26. Although there is a notable decrease in the cost of the DAC system by 2050, it still accounts for more than 73% of overall expenses. Assuming that the costs of electricity and heat remain unchanged until 2050, but the cost of the DAC system reduces to 200 CHF/ tCO_2, calculations estimate that the DAC system cost would represent approximately 60% of the total expenditure.

The implementation of DAC plants and heat pumps requires substantial capital expenditures, making it crucial to maximize their operation time by running them at high FLh. This high availability of electricity is essential for their efficient functioning. To ensure a consistent supply of renewable electricity, particularly in systems reliant on PV and wind energy, the use of batteries becomes indispensable. However, it is important to note that the calculations presented in Table 9 do not account for the inclusion of batteries and do not foresee the usage of grid electricity. The DAC FLh in the case of PV and wind are 1400h and 2200h, respectively. By relocating the DAC plant to a country like Oman, where abundant sunlight is available, the FLh can significantly increase to high numbers, such as 1800 hours. The grid electricity availability is another option to increase the FLh of DAC system. This prolonged operation time has a substantial impact on reducing the LCOD. In 2020, the LCOD decreases to 414 CHF per ton of CO_2 captured, and by 2050, it further decreases to 113 CHF per ton of CO_2 captured.

Table 9: Estimation of LCOD for different systems today and future projection.

	unit	**2020**	**2030**	**2040**	**2050**
Capex	CHF/ t_{CO2}.a	730	350	250	200
Opex fix	% of Capex p.a.	4	4	4	4
El. demand	kWh_{el}/t_{CO2}	250	225	203	182
Low tem. heat demand	kWh_{th}/t_{CO2}	1750	1500	1286	1102
lifetime	year	20	25	30	30
WACC	%	5	5	5	5
$LCOD_{wind}$	**CHF/ t_{CO2}**	**425**	**205**	**143**	**119**
$LCOD_{PV}$	**CHF/ t_{CO2}**	**634**	**292**	**200**	**162**

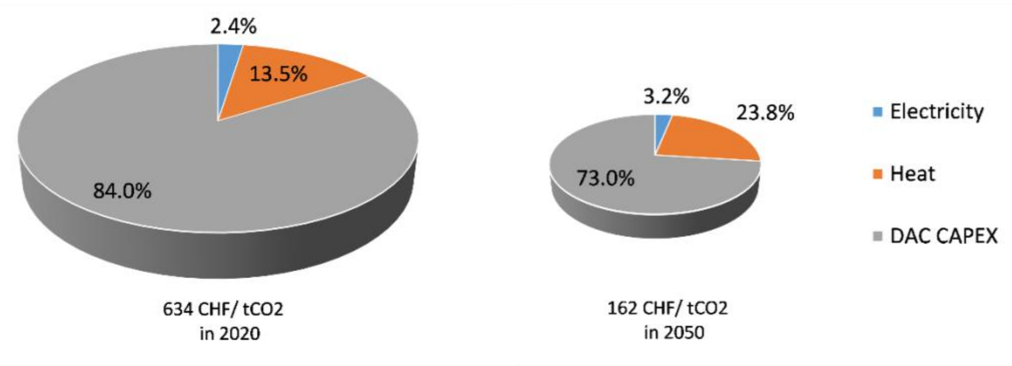

Figure 26: DAC cost break down in 2020 vs. 2050.

2.5.7 Relevant actors

At present, there are 18 operating DAC facilities across Canada, Europe, and the United States; in total, they have the capacity to capture almost 10 $ktCO_2$ each year (International Energy Agency 2022). These facilities primarily consist of smaller-scale plants that focus on selling the captured CO_2 for various applications. The utilization of the captured CO_2 includes its use in PtX processes for the production of chemicals and fuels, as well as its application in beverage carbonation and greenhouse operations. Several companies are at the forefront of commercializing DAC technologies, driving innovation and advancement in this field.

Climeworks AG (S-DAC)[48], established in Switzerland in 2009 as a spin-off from ETH Zurich, has successfully commissioned and operated more than 15 DAC plants across the globe resulting in over 120,000 hours of operational experience. Their low temperature (100°C) capture process is powered exclusively by renewable energy. In Iceland, Climeworks and Carbfix are collaborating to capture CO_2 from the atmosphere at the Orca plant with a nominal capacity of 4,000 tCO_2/year and will capture 36,000 tCO_2/year with the Mammoth plant for subsequent underground storage in basaltic rock through CO_2 mineralization. Mineralization of CO_2 only takes a few years. The Mammoth plant is expected to be operational by end of 2024. Climeworks focuses on storing captured CO_2 permanently underground, providing third-party verified carbon dioxide removal (CDR). Climeworks CO_2 is not used for enhanced oil recovery, a process that utilizes captured CO_2 to extract additional oil from oilwells.

Carbon Engineering Ltd[49] (L-DAC) was founded in Canada in 2009. Their high temperature (900°C) capture process uses fossil natural gas. They have successfully commissioned one pilot plant and

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[48] https://climeworks.com/

[49] https://carbonengineering.com/

recently entered into a licensing agreement with 1Pointfive[50], a subsidiary of Occidental Petroleum, to support the future establishment of a major DAC facility, located in the United States. Making use of Carbon Engineering's DAC technology, this facility looks to eventually reach a capacity for capturing up to 1 million tons of CO_2 annually and aims to start operations in late 2024. The captured CO_2 will either be stored underground or used in the production of hydrocarbons (including enhanced oil recovery) and products like chemicals and building materials.

Global Thermostat[51] (S-DAC), established in 2010 as a spin-off of Columbia University in the United States, has successfully commissioned two pilot plants to date and is actively collaborating with ExxonMobil, one of the world's largest oil and gas companies, to further develop and scale up its capture technology. In April 2021, Global Thermostat entered into an agreement with HIF to supply DAC equipment for the Haru Oni eFuels pilot plant located in Chile[52]. This facility aims to combine captured CO_2 (250 $kgCO_2/h$, equivalent to 2,000 $tCO_2/year$) with electrolytic hydrogen to produce synthetic gasoline.

Numerous smaller companies are also engaged in the development of DAC technologies, including: Hydrocell[53], Infinitree[54], Skytree[55] and Soletair[56].

2.5.8 National and international policies and incentives

In Switzerland

DACS is currently not incentivized in Switzerland in a systematic manner. The Swiss-based company Climeworks has received financial support toward its research and development expenditures as well as its piloting of DACS in Switzerland and abroad. Such supply-pushing policy is, however, not going to be able to deliver the requisite scaling of several 10x factors over time. The Swiss government has indicated willingness to utilize purchases of DACS for eventually achieving net-zero emissions including by balancing the federal government operations' emissions through DACS offsets.

Internationally

DAC's potential to contribute to climate change mitigation is gaining recognition, boosted by new initiatives from both public and private sectors. In 2021, the United States allocated USD 3.5 billion to establish four DAC hubs and introduced a DAC Prize program offering USD 100 million for commercial-scale projects and USD 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, Europe, and other regions.

Beyond such investment support, the internationally most substantial incentive for DACS that has been put in place is the US governments' tax credit 45Q (offering 180 USD/tCO_2 stored).

Nonetheless, to achieve the scaling and associated cost-reduction effects, DACS requires market-based solutions. While Climeworks and other DACS firms are currently also benefiting from voluntary advanced market purchase agreements that secure relevant demand for their credits over the next few years (in some cases up to 8) this also will eventually need to be followed by a broadening demand of buyers for credits, which remain significantly above the levels seen for other mitigation categories.

Ultimately, costs of DACS may have come down significantly to meet gradually rising prices in compliance carbon markets, thereby finally meeting a broad sustained demand. This can include international transactions (under Paris Agreements' Article 6), or emissions trading systems such as the

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[50] https://www.1pointfive.com/
[51] https://www.globalthermostat.com/
[52] https://hifglobal.com/location/haru-oni/
[53] https://hydrocell.fi/en/about-us/
[54] http://www.infinitreellc.com/#about
[55] https://skytree.eu/
[56] https://www.soletairpower.fi/

Swiss ETS and the EU ETS to which it is linked. The EU’s Carbon Removal Certification Framework may ultimately end up offering a pathway for making DACS credits eligible to be traded against ETS allowances. This would – once the costs meet the prices of traded allowances – unlock a very large demand appropriate to the scale that DACS is expected to reach in some projections.

2.5.9 Accounting rules

While there is to date no specific category that DACS would naturally fit, the IPCC guidelines foresee in each sector category subcategories for other types of measures to be included in their greenhouse gas inventories. Absent more specific guidance for DACS, countries are free to report on emissions and sinks as seems most appropriate. They may thus for example report negative emissions in industry (other) from CO_2 directly captured with intent of storing it. For reporting the corresponding CO_2-storage, the same guidelines apply as for conventional CCS (capture at point sources) (Eggelston et al. 2006, Chapter 5).

The Voluntary Carbon Standard (VCS) is adopting a DACS-specific methodology regarding project-based baseline and MRV methodologies for DACS, as part of the framework developed by the CCS+ initiative. This will allow generating projects for the VCM. Climeworks is also working toward inclusion in the Puro Earth standard. Both of these standards offer the option of generating projects for voluntary carbon market transactions. Climeworks is also working toward including DACS projects under the Paris Agreement carbon markets, which allow transactions between two countries including toward their respective Nationally Determined Contributions (NDCs): Perspectives has been supporting Climeworks with the aim of piloting high quality bilateral transactions under the Agreement’s Article 6.2. These efforts may eventually also be adapted for use under the centralised so-called Article 6.4 mechanism under UN oversight.

2.5.10 Open questions

On technological aspects:

- Can't DAC always be converted more efficiently by plants, as there are more co-benefits here? Are there algae, fungi, yeasts or bacteria that convert DAC much more efficiently and cheaply and have additional benefits?

On risks, benefits, costs, potentials and their drivers:

- What exactly will drive down the costs for DAC in the future, the scaling of the production of systems?

On actors, policies and accounting:

- How to ensure that the electricity is renewable which is used for DAC when grid-connected electricity is used?

2.6 CO_2 transport

2.6.1 General description

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 types under the DemoUpCarma[57] project. For quantities from above prox. 1 Mio. t CO_2 per year transport via pipeline is considered to be most cost effective (Becattini et al. 2022) and will be the focus in the DeCIRRA project. However, there are no regulations yet for CO_2 pipelines in Switzerland and the responsibility of building such an infrastructure is with the Cantons.

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", will rely exclusively on ship transport when it opens mid-2024.

One option for Switzerland would be repurposing the old oil pipeline (E50), unused since 2015, which is located at the old Tamoil refinery in Monthey and ends in San Nazzaro (Italy) at the refinery. Without additional modification, the existing pipeline capacity is 400-500 $ktCO_2/y$. With extension (additional compression station and doubling of the pipeline) it can reach 2.5 $MtCO_2/y$. 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 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.

Additionally, 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).

Open Grid Europe (OGE), a German Transport System Operator for gas pipelines, is planning a CO_2 network in Germany connecting German emitters with harbours at the North Sea. The network foresees also a connection to Switzerland at Wallbach, a German-Swiss interconnection point of gas pipelines.

2.6.2 Risks

There are no environmental co-benefits from the transportation of CO_2. For this reason, only the risks are discussed in this section. There are risks for the environment, for example, that the drinking water is contaminated if there are any leakages. This risk was also raised with regard to the Cargo sous Terrain project. Therefore it may well be relevant for a CO_2 pipeline.

Other risks, which are not related to the environment, include 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 may also be the risk of long negotiations as it has to be decided who pays for the part of the CO_2 pipeline which is purely needed for the connection to the other country.

2.6.3 System boundaries, estimates of costs, potentials, 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.

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

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 27). 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. 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/ t CO_2.

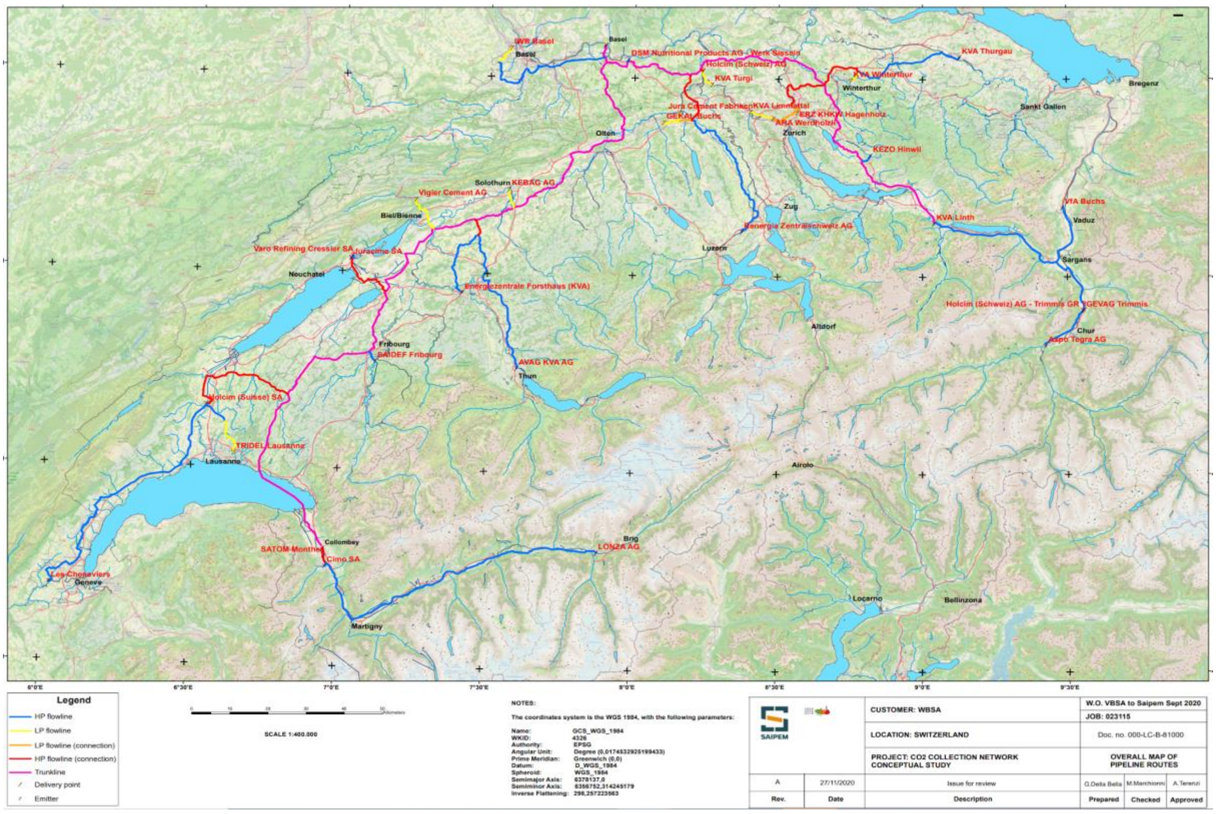

Figure 27: CO_2-Network Map (SAIPEM 2020)

Table 10: 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 recent 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 is the pipeline built and managed?

2.6.4 Relevant actors

Most relevant actors were already mentioned in the section on BECCS, because transport is important for all the big CO_2 emitters like waste incinerator plants, cement production plants or heating and power production plants driven by wood and others.

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[58]" (Eidgenössischen Rohrleitungsinspektorat) for the technical supervision. Further there will be relevant Canton or/and further national authorities involved. Further relevant actors are the operator(s) of the CO_2 Pipeline and their shareholder(s).

In this respect the Swiss gas industry is an important partner, given that when fossil gas pipelines are not used anymore they will be able to make use of their expertise for decarbonisation, and also Swisstopo as they both know the Swiss underground very well and the former has experiences with pipelines.

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.

Cargo Sous Terrain has experience in the financing and planning of large transport infrastructure, which may also serve to include part of the CO_2 pipeline.

Internationally there are some relevant companies that plan and built pipelines in the surrounding countries, like TES[59]. In Europe, but especially in Germany, the private company TES is pushing ahead with the construction of a pipeline network for the transport of green H_2 in the form of methane (Green Cycle). In order for the use of methane to be CO_2-neutral, the CO_2 must be captured from the methane, transported away and converted back into new synthetic methane (e-NG). Therefore, TES and OGE are jointly 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. TES aims to supply Energie 360° with around one TWh of renewable synthetic methane (e-NG) annually from 2027. In return, Energie 360° wants to supply TES with renewable CO_2.[60] A partnership was signed with VBSA to decarbonise waste-to-energy plants in Switzerland, which emit around 4 million tonnes of CO_2 per year. [61]

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[58] https://www.svti.ch/en/federal-pipelines-inspectorate-fpi

[59] https://tes-h2.com/de

[60] https://tes-h2.com/de/news/energie-360-und-tes-schliessen-partnerschaft-um-gruene-energie-an-industrie-zu-liefern

[61] https://tes-h2.com/de/news/tes-und-vbsa-unterzeichnen-partnerschaft-zur-dekarbonisierung-von-kehrichtverwertungsanlagen-in

2.6.5 National and international policies and incentives

In Switzerland

Legal basis for CO_2-transport demand

Switzerland has adopted a long-term climate strategy which is reliant on the transport and storage or utilization of CO_2 in part domestically, but also at a significant scale abroad (given very limited capacity for CO_2-utilization and storage inland). The new Federal Act on Climate Protection Goals, Innovation and Strengthening Energy Security (KlG)[62] 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.

Swiss policy planning relies on projections and scenarios offered by the commissioned study *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. According to this study the volume of anticipated transport amounts to 7 Mio tons of CO_2 annually (by 2050) unless some of the CO_2 can be stored directly at the site of capture.

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) 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 capitalized on Art. 81 of the Federal Constitution[63] to put forward the vision of underground rail transport combined with pipeline gas transport capability.

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 land-ownership. The legal permits need to be discussed and planned by the ERI / SFOE, right now the rules and specifications are unclear.

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

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[62] https://www.fedlex.admin.ch/eli/fga/2022/2403/de

[63] "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".

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 11).

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 Law (Schweizerische Eidgenossenschaft 2022). 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 recognized on the company's 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 11: Possible variations of organising and financing 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 center 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 has to 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" (CO2 TSO) constructs the whole pipeline and gets a usage fee by 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 in order to see if it could be a solution as well for Switzerland.

Internationally

There are no examples internationally of comprehensive regulation regarding CO_2-transportation at scale. The US has a long history of problematic approval processes for gas pipelines and the permitting processes for CO_2-transport, which have begun in context of the regional DAC hubs appear to experience the same challenges.

In Germany, Open Grid Europe (OGE) has set up an internal project to prepare a specification framework which can be the base for a regulation/permitting process. It is foreseen that there will be an exchange between them and technical experts from Switzerland including the ERI (Eidgenössisches Rohrleitungsinspektorakt).

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 utilization 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.[64] The initial problem was that the first isotainer of CO_2 arriving in an Icelandic port was rejected for not properly being declared and as there are regulations against the disposal of foreign wastes in the country. The import 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;

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[64] See the project website: http://www.demoupcarma.ethz.ch/

varying national legislation may pose a particular challenge that may be different in each combination of two countries 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 emission under International Maritime Organisation (IMO).

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 and 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 harmonization 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 harmonized 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 standardization

For interoperability, all forms of CO_2 transport will require progress toward standardization 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 standardization that achieves compatibility across CO_2 transport elements in Europe. Lack of harmonization hinders cross-border activities and creates additional uncertainty in a sector that is already considered high-risk for investments (Neele et al. 2013). Standardization 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 need to mirror also 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, see EU (2022)) offer significant opportunities for the development of CO_2 transportation pipelines and other CO_2 transport infrastructures. 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 authorization processes, streamlining the development and deployment of CO_2 transport infrastructure.

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.

2.7 CO_2 storage

2.7.1 General description

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. This chapter will explain the current status of this topic, what storage options exist and how high the potential for this is estimated to be worldwide and in Switzerland.

According to the IPCC (2005), there are six different geological storage options (see Figure 28 Figure 28), 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 the one hand 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 there 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.

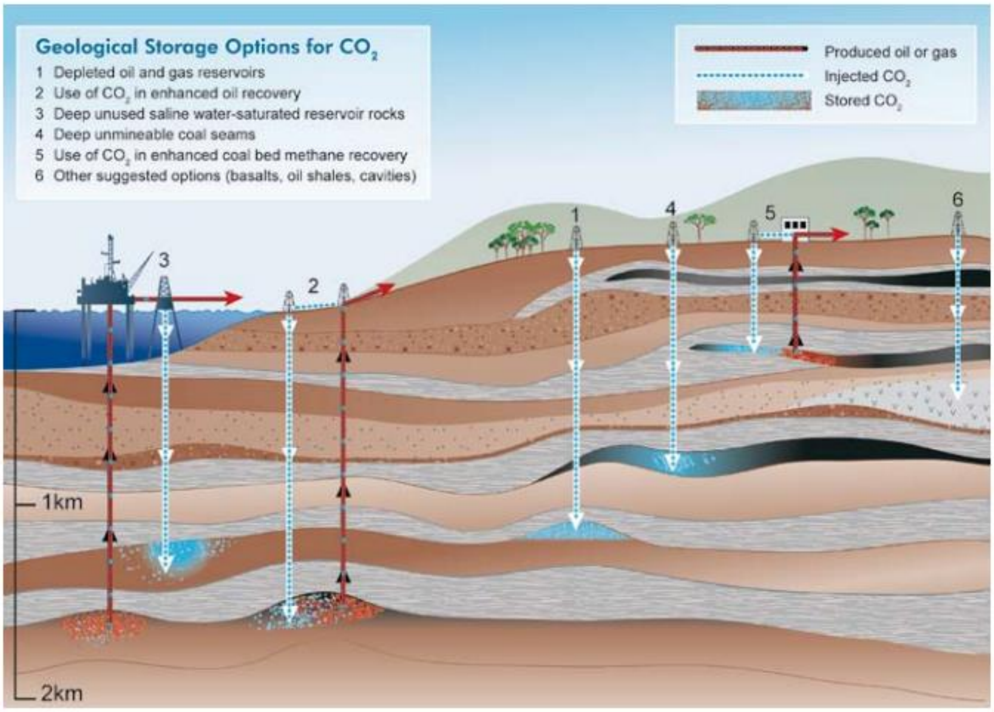


Figure 28: Options for storing CO_2 in geological formations (Intergovernmental Panel on Climate Change (IPCC) 2005)

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

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.

2.7.3 Co-benefits

The only currently known co-benefit 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 on 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.

2.7.4 Risks

According to Christophe Nussbaum of swisstopo, the main risks are as follows (see also Figure 29), 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.

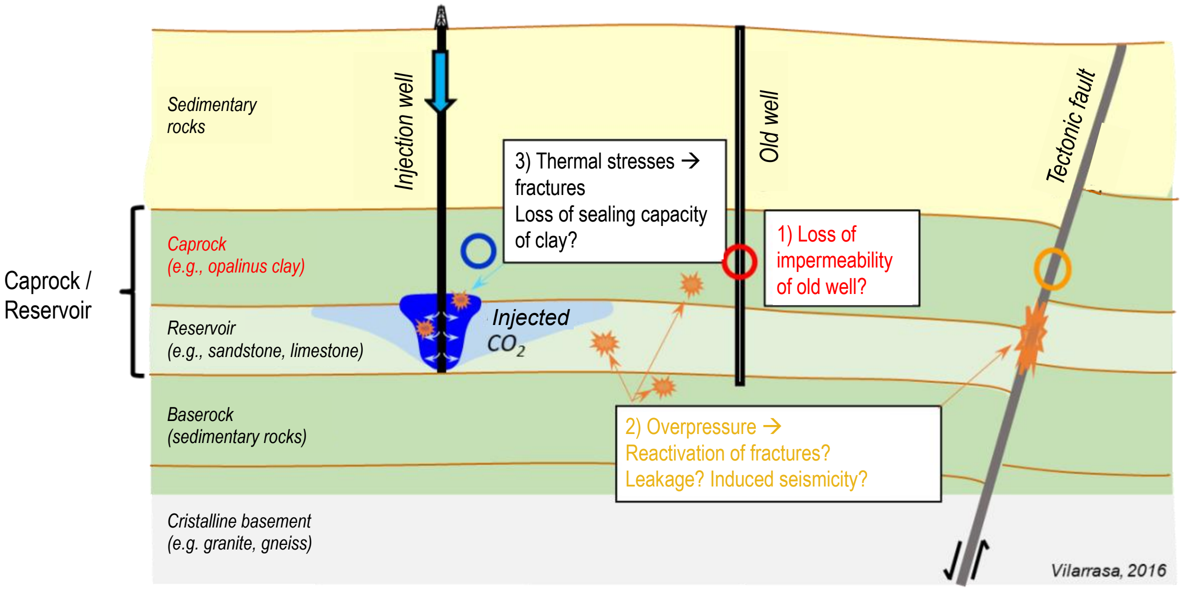


Figure 29: Potential causes of induced microseismicity and seismicity related to geological carbon storage (Vilarrasa 2016)

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

Risk of non-acceptance by the population, whereby it can be assumed that acceptance for offshore storage is higher than for storage on land, especially if this is populated.

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). 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 workshop).

2.7.5 Estimates of costs, potentials, and main drivers

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 12), 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.

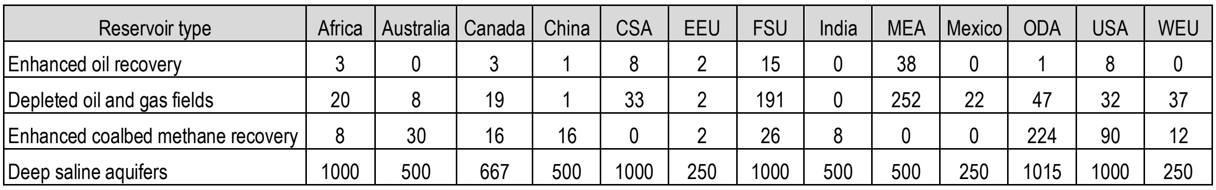
Table 12: Costs of storing CO_2 underground (Kemmler et al. 2021, p. 34)

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

Globally

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.

Table 13: Estimated geologic storage potential across underground formations globally ($GtCO_2$) (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

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

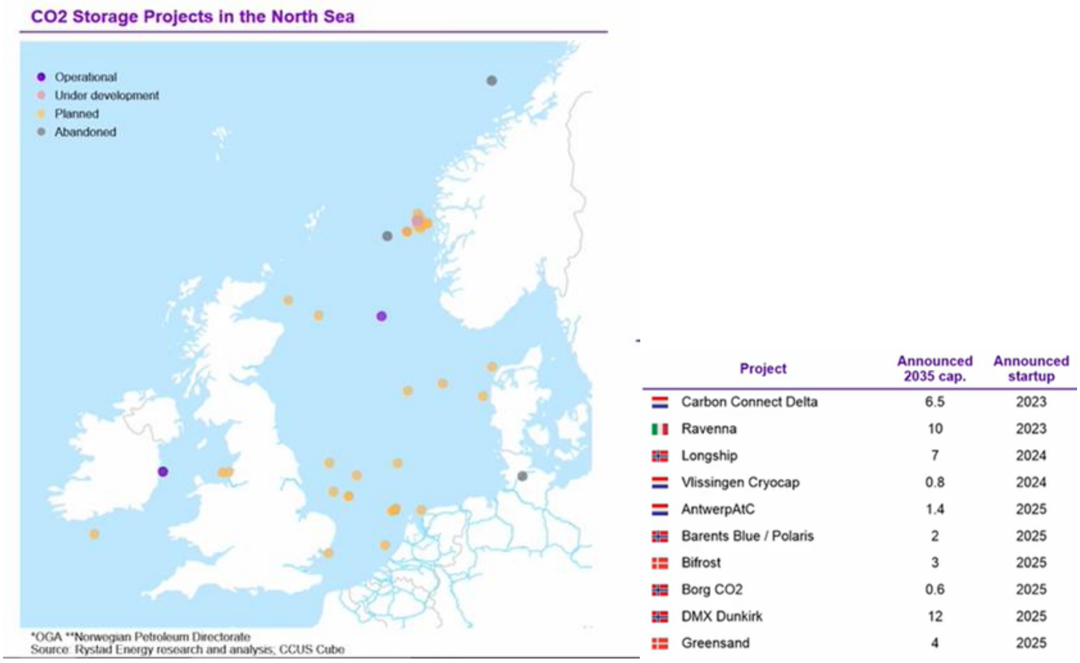
- 27 projects are in operation and store 36.6 $MtCO_2$/year.
- 62 further projects are either under construction (n=4) or in the advanced development phase (n=58).
- A further 44 projects are in an early development phase.

If all these projects are successfully implemented, the cumulative storage potential would be around 150 $MtCO_2$/year.

In Europe

As already mentioned in Section 2.6, the company TES is planning the construction of a pipeline network for the transport of green H_2 in the form of methane. CO_2 pipelines are also being planned and constructed as part of this project. TES is a globally active company that belongs to OGE with the aim of supporting decarbonisation with the help of green hydrogen. It is currently building energy supply and import centres in Germany, Benelux, France, the Middle East, Canada, Australia, North Africa, South Africa and the United States to integrate and optimise global supply chains. TES has entered into a partnership with Energie 360° and the VBSA. TES intends to supply Energie 360° with around one TWh of renewable synthetic methane (e-NG) annually from 2027. In return, Energie 360° wants to supply renewable CO_2 to TES. TES and OGE are jointly developing a 1000-kilometre-long CO_2 transport network in Germany that connects the TES Green Energy Hub in Wilhelmshaven with several industrial sites to which the CO_2 will be shipped and then sequestered or reused for the production of e-NG.

Strategically important locations in Switzerland, such as Basel, can be connected to this infrastructure by train or pipeline.



Project	Announced 2035 cap.	Announced startup
Carbon Connect Delta	6.5	2023
Ravenna	10	2023
Longship	7	2024
Vlissingen Cryocap	0.8	2024
AntwerpAtC	1.4	2025
Barents Blue / Polaris	2	2025
Bifrost	3	2025
Borg CO2	0.6	2025
DMX Dunkirk	12	2025
Greensand	4	2025

Figure 30: CO_2 storage projects in the North Sea (Rystad 2022)

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 of CO_2 could be stored in molasse in the Western Jura, with 0.7 Gt of CO_2 in the upper Muschelkalk. A more recent study by the University of Bern comes to 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 31). According to the Energy Scenarios 2050+, 3 million tonnes of CO_2 are to be stored domestically in 2050 (8.6 million tonnes of 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.

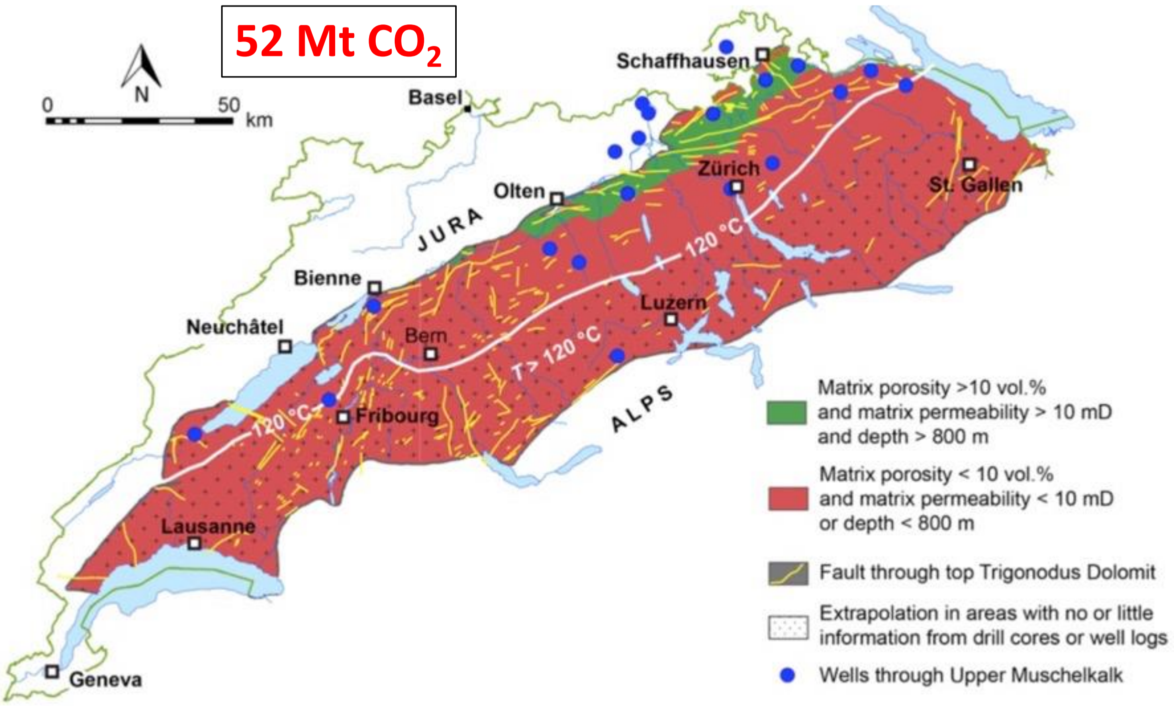


Figure 31: Potential for CO_2 storage in the Upper Muschelkalk aquifer, Switzerland (Diamond 2019)

2.7.6 Relevant actors

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.

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.

2.7.7 National and international policies and incentives

In Switzerland

So far, there is no policy incentivizing CO_2 storage in Switzerland. At the moment, Swisstopo is carrying out research in order to produce an updated estimate of the domestic storage potential.

Internationally

Germany has a law on CO_2 storage (Kohlendioxid-Speicherungsgesetz or KSpG), which allows for researching, piloting and demonstrating CO_2 storage facilities in Germany, however with limits on the total storage volume across the country and within individual projects. Each federal state is entitled to designate the areas in which CO_2 storage is allowed. Strict environmental requirements are established for the approval of storage projects, as well as comprehensive monitoring plans.[65]

According to the IEA Climate Policies database, several other countries have adopted legislation to regulate the storage of CO_2, including Australia (at the subnational level in Queensland and Victoria), Canada (subnationally in Alberta and Saskatchewan), Indonesia (focused on EOR and use of depleted oil and gas fields), Norway, UK, and the US (where as of 2017 at least 21 states had adopted legislation related to CCS activities, according to Cleveland (2017)). Such legislation typically includes provisions regarding ownership of the underground pore space, exploration and use rights, safety, permitting, and post-closure obligations, and assigns responsibility for monitoring and liability. Often, a fund is created to support long-term monitoring and potential remediation costs in terms of leakage.

At EU-level, the 2009 Directive on the geological storage of carbon dioxide[66] establishes uniform minimal requirements for CO_2 capture, transport and storage in the member states, including for example specific requirements for the selection and operation of storage sites and for their monitoring, which aim to prevent, minimize and if necessary remedy any CO_2 leakage.

Because CO_2 can be stored in the seabed, the Convention for the Protection of the Marine Environment of the Northeast Atlantic Ocean (OSPAR) as well as 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 provided their demands on the protection of the marine environment are met.

EU projects of common interest are shaping up to be a relevant avenue to accelerate storage site planning and development under favourable regulatory and economic conditions. Notably, projects like Northern Lights have been preselected for EU funding, with €4.25 million allocated for Phase 2 FEED (Front-End Engineering Design) studies. Northern Lights, listed as the 5th PCI, boasts 18 promoters and 22 affiliates, representing significant capture potential of approximately 19 million metric tons per annum (Mtpa) by promoters alone, and around 32 Mtpa when including affiliates. These promoters span across Norway, France, Belgium, the Netherlands, Germany, Sweden, and Finland, showcasing the diverse range of participants engaged in CO_2 capture and transportation. Standardization efforts and collaboration on capture sites further enhance the prospects for efficient and effective CO_2 transport infrastructure development within the PCI framework.

2.7.8 Outlook

Reliability and trust are required from the storage provider, as well as competence and flexibility in CO_2 offtake. Ideally some own national capacity as well as several international providers would be available so that there are fewer dependencies and some competition. However, Switzerland seems to have only little own storage capacity and will either be reliable on storage sites in North Sea (Northern Lights, Iceland) or Italy (Ravenna), to reach those storage sites it will need to use existing gas pipelines either through Germany or from Monthey (CH) to Genoa (IT).

With this rather little storage capacity in Switzerland, it is important to legitimize storage abroad. If storage abroad occurs, state treaties or framework agreements are needed. In addition, long-term contracts between emitters and storage providers are a prerequisite.

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[65] https://www.umweltbundesamt.de/themen/wasser/gewaesser/grundwasser/nutzung-belastungen/carbon-capture-storage#rechtsvorschriften-fur-ccs

[66] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0031

3 Actors, projects and policies

3.1 Actors

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 32). 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 32. The rows contain the various actors involved in all of these processes.

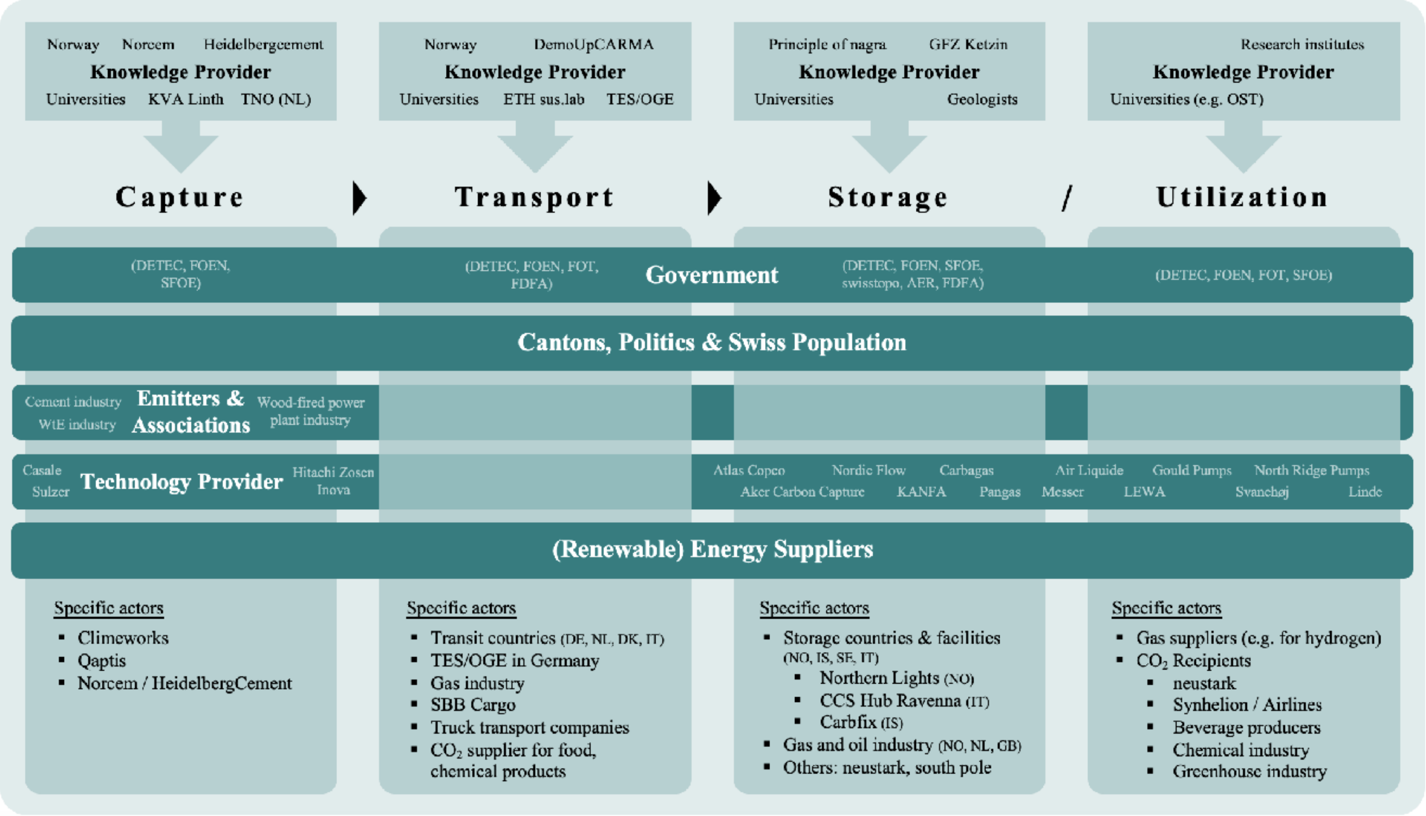

Figure 32: Relevant CCS and CCU players in Switzerland along the value chain (Tanner 2022)

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 33). 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.

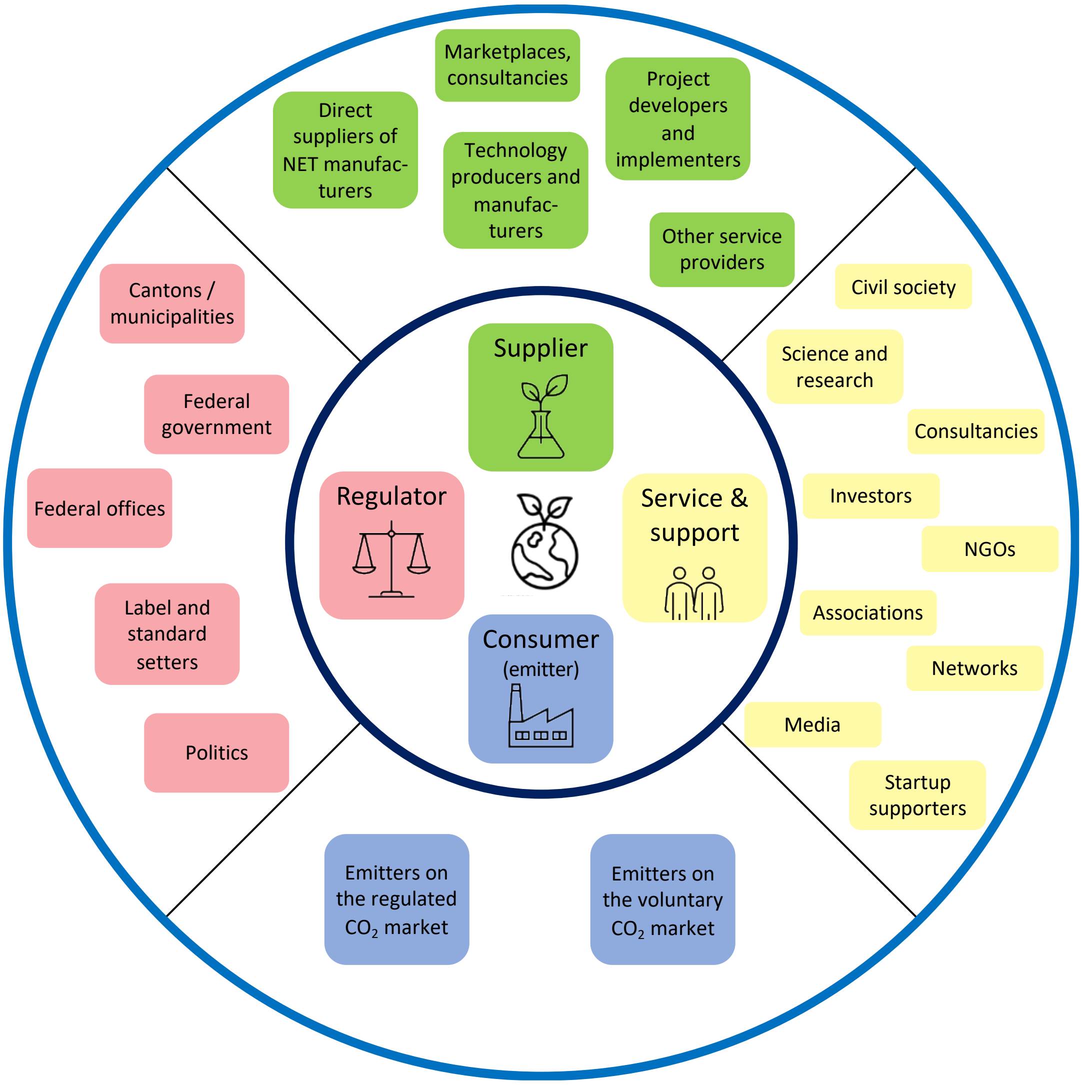

Figure 33: Roles in the NET actor network

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 34, 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.

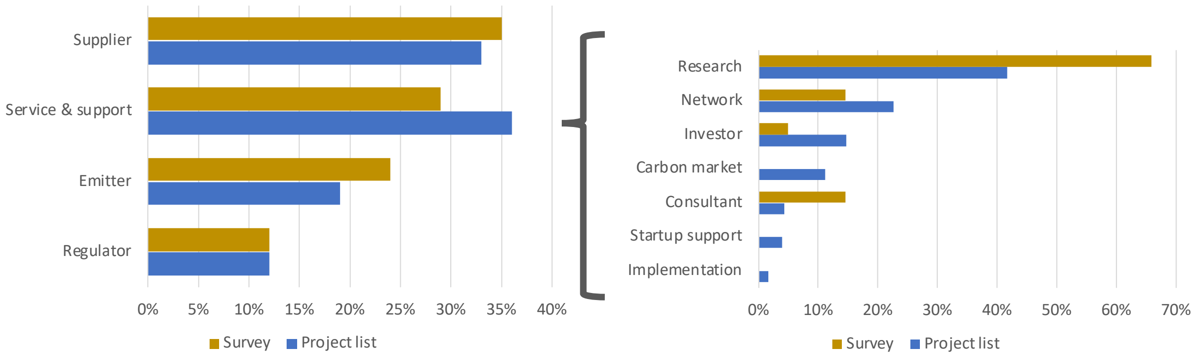

Figure 34: Roles of DeCIRRA actors in the list of 711 entries compiled for DeCIRRA, compared to the 139 survey participants

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 35), with BECCS and CCS/CCU being mentioned the most.

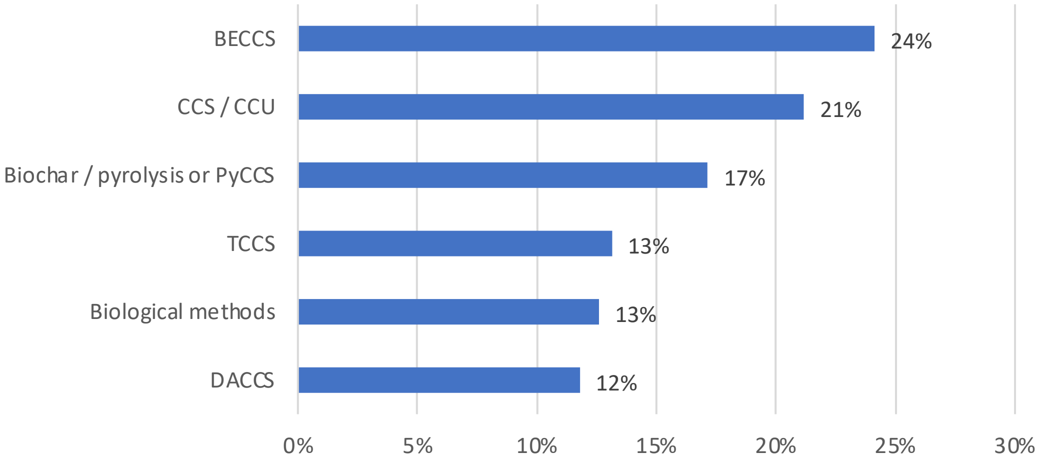

Figure 35: Which of the NET technologies is currently relevant to your work or will be in the near future? Multiple answers possible

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 36).

The survey shows that there is already close cooperation between many stakeholders (Figure 37), 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.

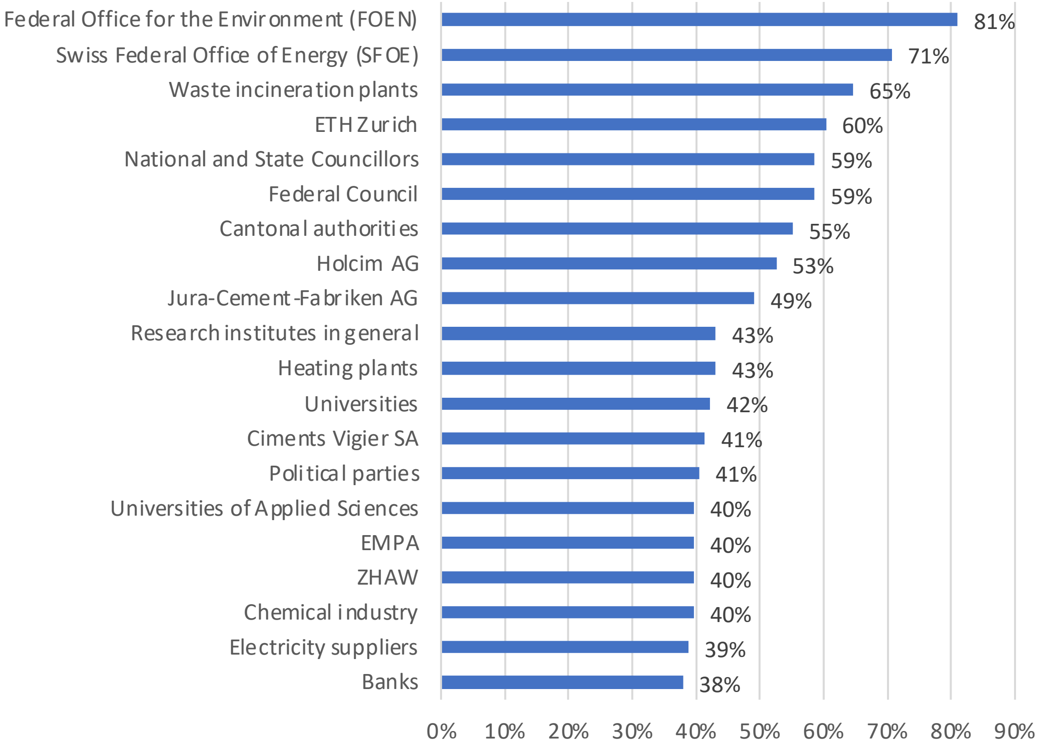

Figure 36: Actors rated as very important for Swiss CDR policy

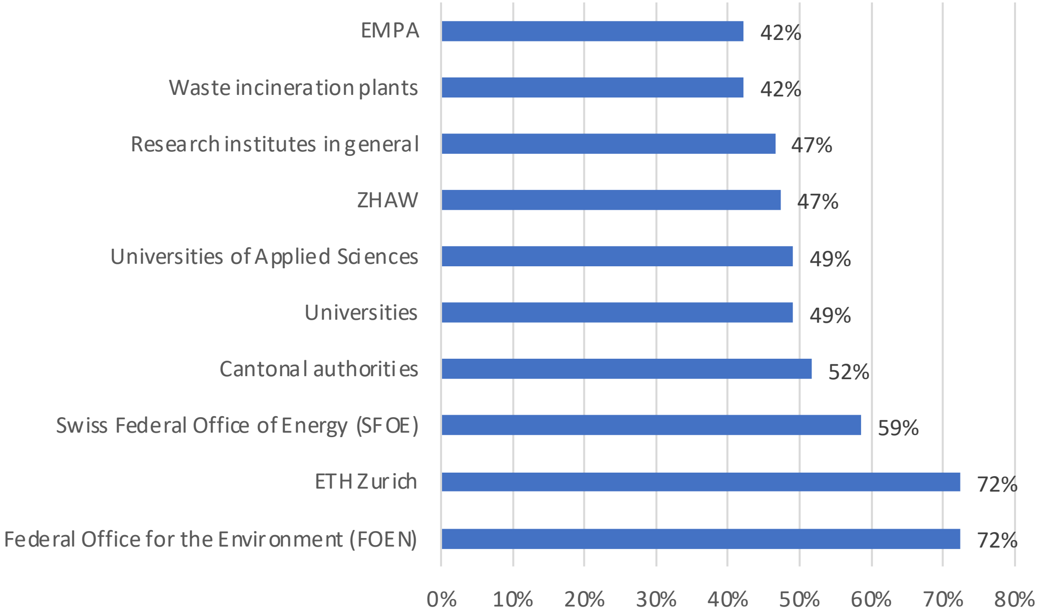

Figure 37: Actors that were mentioned particularly frequently in response to the question of whether there is close cooperation.

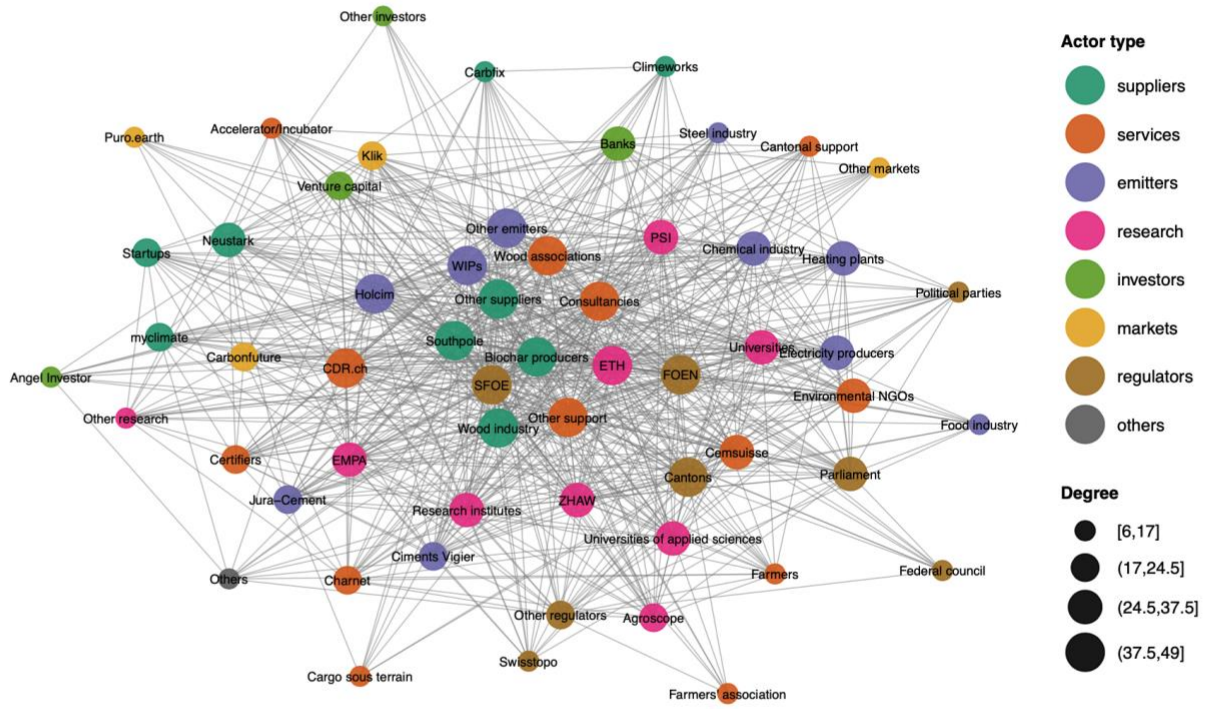

Figure 38: The close cooperation network among the interviewed Swiss NET players

Figure 38 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.

To summarise, it can be said that many of the Swiss NET players are already very well networked. As part of the project, it will now be important to show where the network can still be improved and which key players need to be further involved.

3.2 Swiss CDR projects

As part of DeCIRRA, current CDR projects were screened and compiled in a list.[67] 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. This list was compiled in spring 2023 and we will endeavour to update it once a year if possible during the project period.

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 are still ongoing, of which around 16 can be categorised as permanent projects, which should perhaps rather be classified with the actors. These

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[67] https://docs.google.com/spreadsheets/d/1GpVuKlKZNSLFpDhqIazacJHAyr24nraBiZ8xjHp_cFs/edit?usp=sharing

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.

The projects were categorised according to their focus, e.g. whether they have a technological or ethical 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 39 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.

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 helps us to identify other relevant experts.

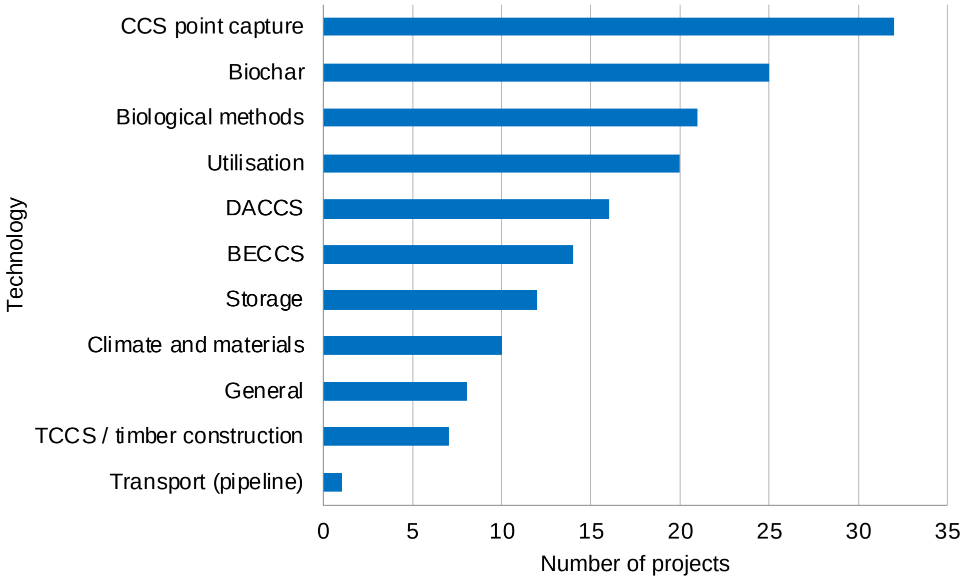

Figure 39: Number of screened projects dealing with the different technologies. Projects in Climate, Material and General could not be allocated to a certain CDR topic.

3.3 Stakeholder policy preferences

In the previous chapters, for each of the four CCUS 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.

A very complete source of information on policy support for CCUS approaches is the IEA Policies database.[68] Of the 145 policies and measures around the world identified in this database to pertain to CCUS technologies (including those policies in force, ended, planned and announced), the large majority provide some kind of direct funding for investment (43 policies) or for R&D and demonstration projects (35 policies). Other common policies establish a regulatory framework for CCUS technologies, frequently comprising the permitting, ownership, monitoring and long-term liability for storage sites (31 policies), or a strategy or target for their deployment (16 policies). Further support policies include tax credits or other

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[68] https://www.iea.org/policies

types of tax incentives for CCUS investments and research (in the US, Austria, Canada and Malaysia), operating subsidies for CCUS plants (in Australia and the Netherlands), emissions standards for coal power plants that are expected to require the use of CCUS (Canada), carbon credits for CCS applications (California), as well as a planned reverse auction for biogenic CCS facilities in Sweden.

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 incentivize 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 40 presents an overview of these approaches, as well as several existing examples for each of them.

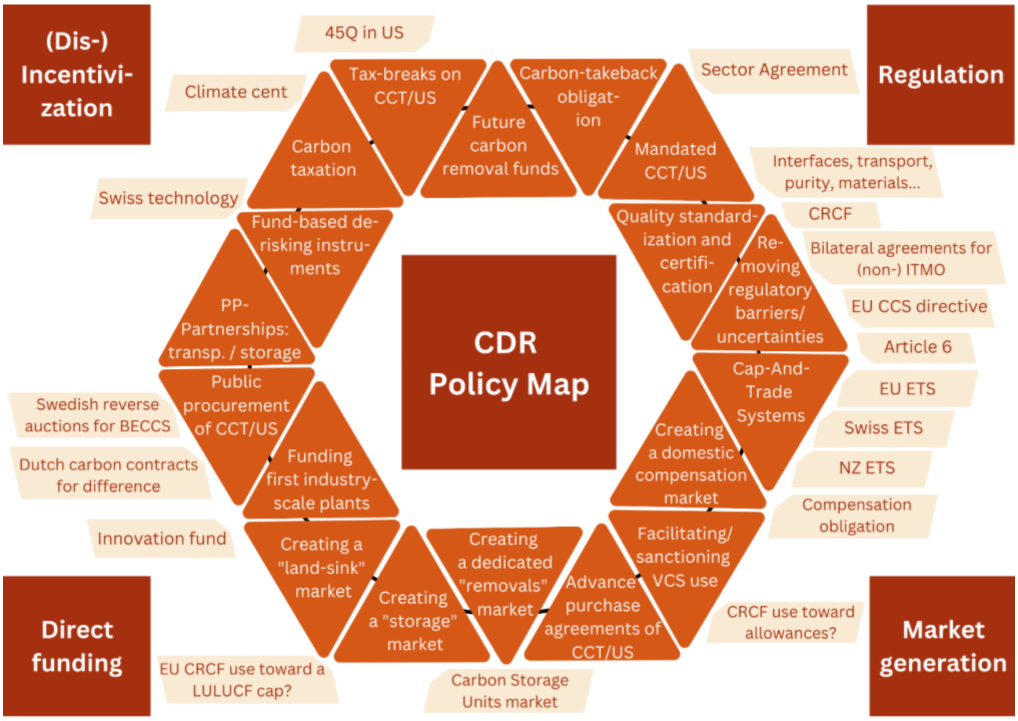

Figure 40: Overview of potential policy instruments to support CCUS approaches (Pape et al. 2023)

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 41, 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.

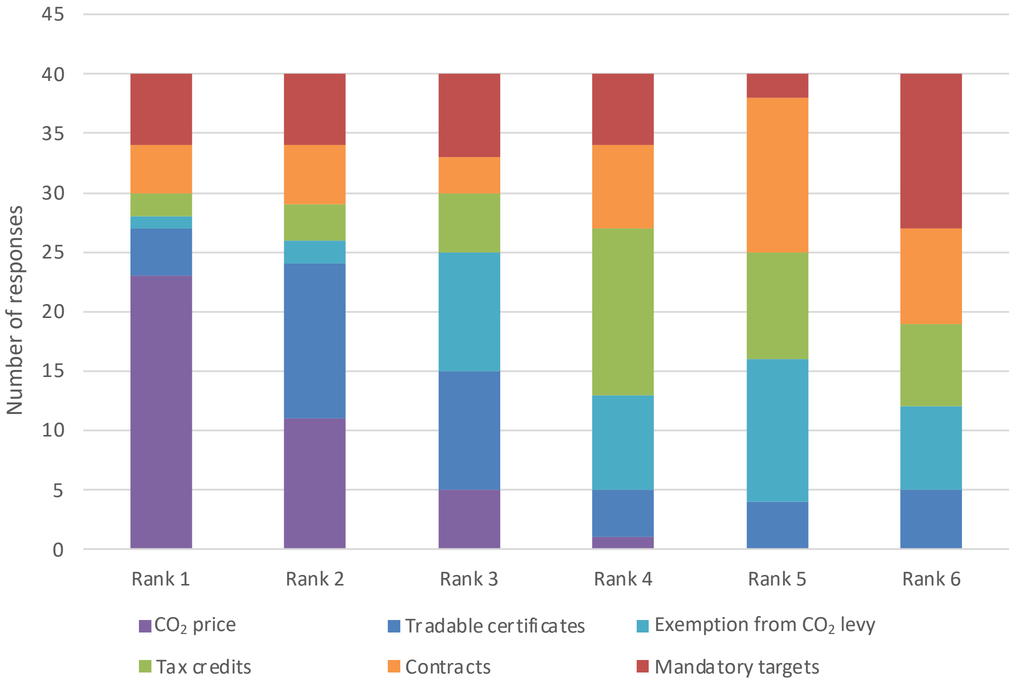

Figure 41: Policy ranking for TCCS (respondents from all stakeholder groups)

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, as shown in Figure 42, the policy that was most frequently ranked best across all respondents were **mandatory targets**, followed by the CO_2 price. 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.

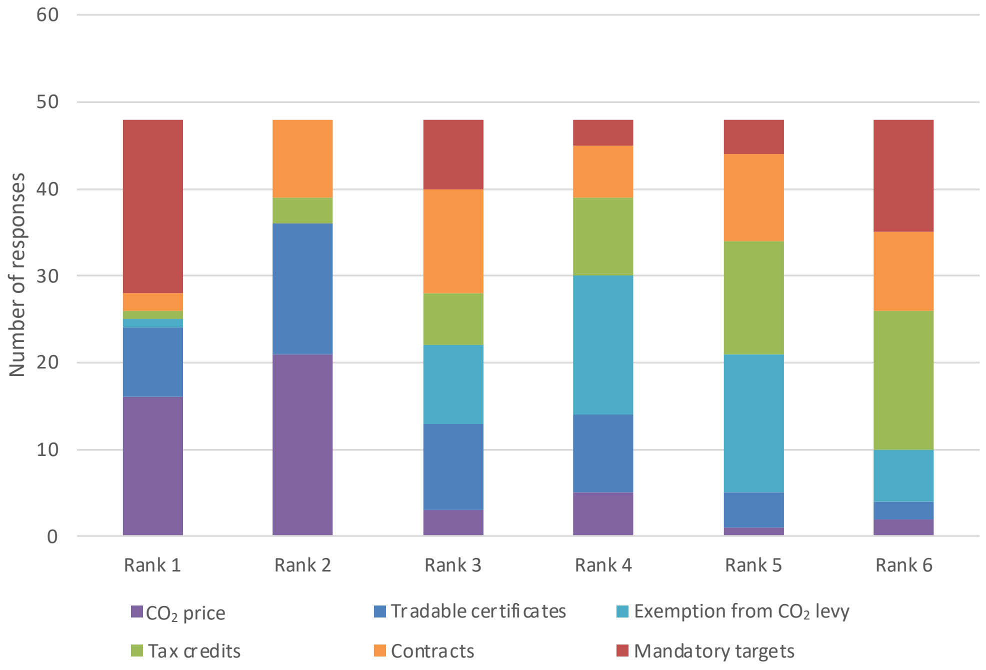

Figure 42: Policy ranking for biochar (respondents from all stakeholder groups)

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 (Figure 43). Accordingly, as shown in Figure 43, 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.

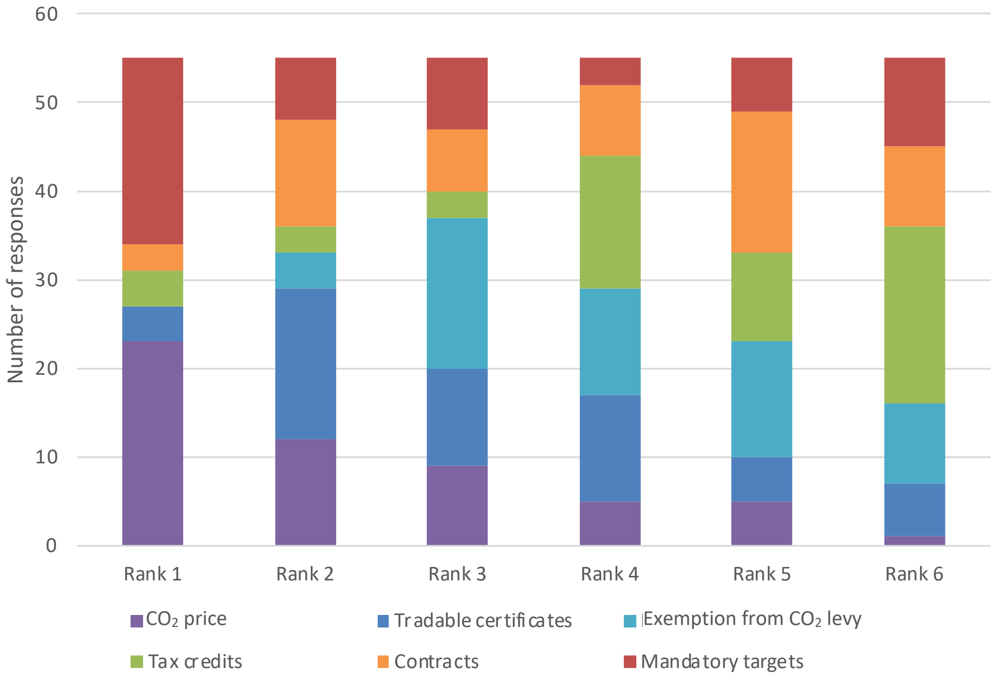

Figure 43: Policy ranking for BECCS (respondents from all stakeholder groups)

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 (see Figure 44). 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.

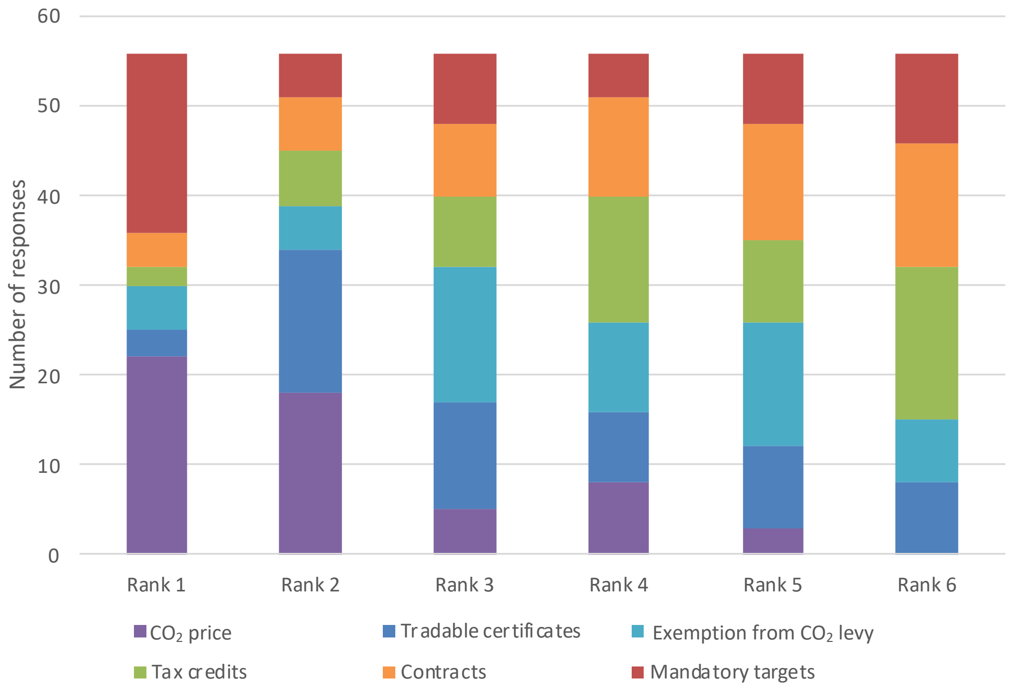

Figure 44: Policy ranking for CCS/CCU (respondents from all stakeholder groups)

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 (Figure 45). 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.

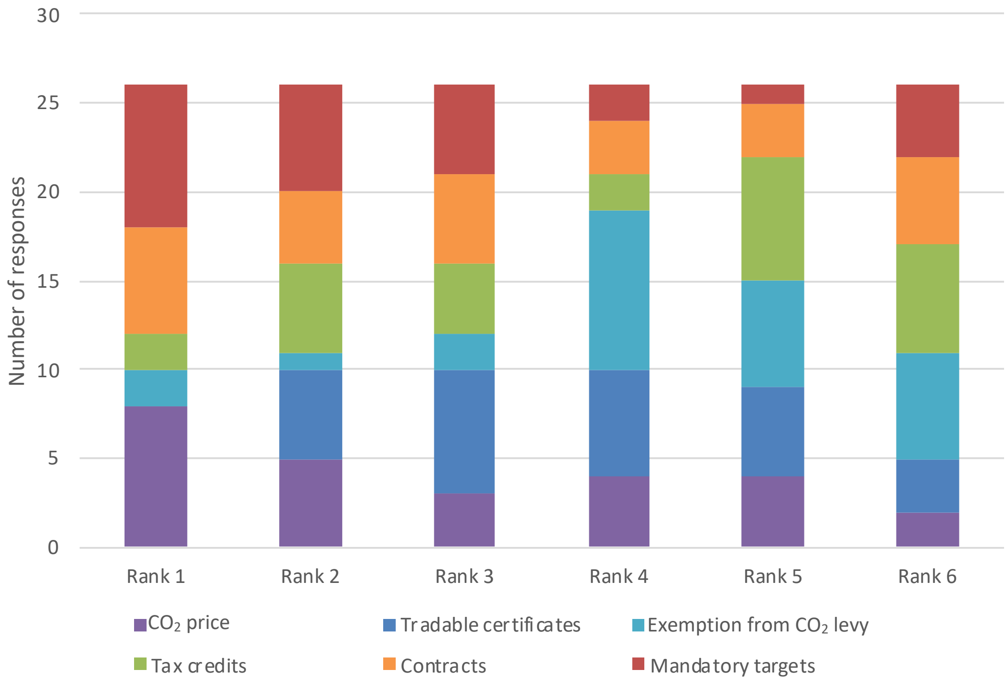

Figure 45: Policy ranking for DACCS (respondents from all stakeholder groups)

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 (Figure 46). 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.

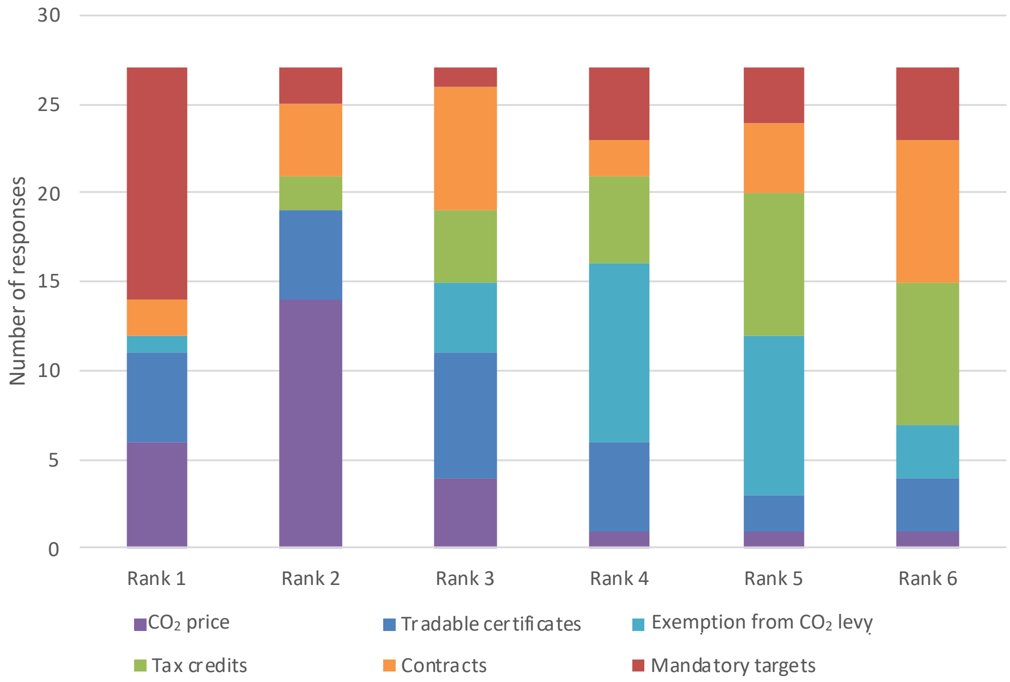

Figure 46: Policy ranking for biological CCUS methods (respondents from all stakeholder groups)

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. Table 17 consolidates the responses (mostly in German) about necessary policy measures until 2030, while Table 18 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 19 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.

4 Outlook

This section summarises the identified knowledge gaps in the three areas (technology, policy screening, accounting) and explains the further procedure, which will primarily deal with scenarios, to answer the SP3 research questions.

4.1 Technology screening and CO_2 Removal Cost Curve

The **aim of DeCIRRA SP3** is to answer the question: What would be the most efficient combination of CCUS and NET, when would be the time in each case to invest, taking into account international developments (e.g. availability of CO_2 storage sites and H_2 import)? How are (co-)benefits (e.g. improved soils through biochar) and risks (e.g. due to land and water use) taken into account in the investment analysis?

Status of interim report: For each of the four CCUS approaches, the interim report contains cost estimates that are based on the existing literature for biochar, BEC, transport and storage, on the project members' own estimates for TCCS, and own analyses of the main determinants of costs (i.e., renewable electricity generation) for the case of DAC. The estimates of potential are based partly on our own analyses (TCCS) and partly on existing literature, whereby for BEC and biochar they are heavily dependent on the biomass available and, in the case of biochar, the biomass that can is permitted to be used.

Co-benefits and risks were identified for all technologies and are summarised in the following two tables, Table 14 and Table 15.

Table 14: Co-benefits of the analysed CCUS technologies

Co-benefits	Climate-relevant	Other environmental	Other sectors
Biochar	Soils: Reduction of N_2O Enhanced C storage due to microbes Reduction of methane: Sewage plants, manure, cows, rice cultivation	Animals enhanced feeding stuff uptake Enhanced growth of plants (due to better water retention, root development) Reduction of bad smells, micro plastic, toxic	Fills the cracks in concrete
TCCS	Enhanced growth of trees Improves climate resilience of forests Less risk of capture reversal due to forest fires (houses are better protected against fire compared to wood in forests)	Enhanced biodiversity Reduced building material waste	Substitution effect (steel, cement)
BECCS	Much higher CO_2 concentrations compared to DACCS, therefore lower energy demand Double systemic benefit (flexible energy storage, or negative emissions)	Better air quality if other pollutants besides CO_2 are captured	Industry becomes more independent and flexible, e.g. from carbon imports, if production of synthetic energy with captured CO_2
DACCS	No long-distance transport of CO_2 is needed if captured at storage site, which reduces energy need for transportation	Better air quality if other pollutants besides CO_2 are captured	Industry becomes more independent and flexible, e.g. from carbon imports, if production of synthetic energy with captured CO_2

Table 15: Risks of the analysed CCUS technologies and infrastructure needs

Risks	Climate-relevant	Other environmental	Other sectors
Biochar	Risk of deforestation Overexploitation of forests with unsustainable raw material procurement Improper pyrolysis processes or biochar utilisation Risk of stored carbon being released back into the atmosphere	Lower yield due to reduced soil fertility and nutrient availability due to increased acid buffering in the treated soils and potentially ecotoxic effect Negative effects on health due to and increased release of substances	
TCCS	Risk of deforestation or overexploitation of forests if raw materials are not procured sustainably Increase in wood-fuelled heating networks leads to a shortage of energy wood and could result in non-residual wood being burned		
BECCS		Chemical additives (e.g. amines) and the loss of greenhouse gases into the atmosphere (e.g. methane slip)	High energy requirements for separation can lead to gaps in the supply of thermal and electrical energy
DACCS		Land use, water consumption and potential release of chemicals used in capture and storage	
Pipeline	Leaks in the pipeline	Contamination of the groundwater	
Storage	Higher consumption of fossil energy due to price reduction through injection of CO_2 into oil reservoirs Leakages in the reservoir or during injection	Contamination of the groundwater	Seismic risk (for earthquakes) due to CO_2 injection into the reservoir

In-house analyses of the investment and running costs for biochar and BEC should be further developed and estimated together with the implementation partners. Different variants for the allocation of these costs to the products, some of which are generated simultaneously, should be carried out. The scenario analyses will also provide further information on the potentials; a separate workshop will be held on this in November 2023.

Based on the technology screening, a so-called "pseudo merit order" curve or CO_2 Removal Cost Curve will be created at the end of the project. This graphically depicts the potential and costs for CCUS or NET and emission reduction measures. Each bar represents an individual measure in relation to its contribution to abatement. The cumulative annual potentials are plotted on the abscissa and the respective specific costs on the ordinate. Reductions on the left-hand side include negative emission approaches such as biochar, wood construction, BECCS and on the right-hand side reduction approaches such as CCS, which are sorted like a reduction curve.

This includes the one-off investment and operating costs compared to the reference case for a specific year in the future (e.g. 2030, 2035, 2050). No marginal costs are considered, hence the name pseudo merit order. The investments and savings are discounted to the present value. If the savings exceed the investments, the costs are negative and lie below the abscissa. Certain negative emission measures also lead to indirect savings, so-called co-benefits (e.g. fertiliser savings through biochar), which are shown separately.

This analysis takes a macroeconomic perspective and therefore attempts to include all positive and negative social impacts (co-benefits and additional risks) insofar as they can be quantified. These are shown separately depending on whether they are negative emissions or reductions in greenhouse gases. Normally, a different interest rate is applied in the private sector investment assessment than in the macroeconomic assessment, as the latter involves longer time periods with intergenerational effects.

Depending on the approach, there are significant differences between national and international potential and costs, which is why a distinction must also be made here. As shown in Section 2.7, Switzerland only has limited geological storage potential. The potential of CCS approaches therefore depends largely on whether storage capacities abroad can be included. Table 16 summarises the technical potential that could be achieved with each of the CCUS technologies considered in the various sections of this report.

Table 16: Potentials of the analysed CCUS technologies

	Biochar	**Wood construction (TCCS)**	**BEC(CS)**	**CO_2 storage potential**
CO_2 storage potential ($MtCO_2e$)	2.2 per year	CH Wood: 1.2 per year Cumulative: 36 till 2050 CH Import: 3.52 per year Cumulative: 103 till 2050	CCS cement: 2.4 per year (10% biogenic) WIPs: 4.4 per year Wood-fired power plants: ? Water treatment plants: 0.17 per year Chemicals: 0.75 Refinery: 0.3	Switzerland: 52 in 2040? Europe: 102 in 2035, from which: - Netherlands: 8.7 - Italy: 10 - Denmark: 7 Offshore Potential: - Norway / UK: 160'000 (long-term)
Starting material	2.8 Mt dry matter	CH Timber: 2.1 – 3.15 million m^3 wood CH Import: 8.3 million m^3 wood	Waste and wood	-
Drivers	Framework conditions about which starting materials are usable	Timber availability at home and abroad Sawmill capacity, e.g. also for hardwoods Construction activity (interest rates, standards, ...)	Circular economy Wood availability Capture: space, heat, electricity, transport from point source	Bilateral agreements for CO_2 transport and storage Standardisation and regulatory framework

The presentation in the form of a CO_2 Removal Cost Curve (see Figure 47) has the **advantage** that it shows which policy instruments are more suitable for which approaches (Grubb et al. 2013):

- Measures that would already be economical from the perspective of society as a whole are on the far left because they show negative costs, e.g. through high energy savings or very worthwhile co-benefits. These should actually get off the ground without funding. Nevertheless, some of them require political intervention, e.g. the removal of existing barriers such as regulation or the offsetting of negative external effects that have not yet been priced in. For example, the negative effects of fertiliser use can cause high costs. If these were priced in, biochar would be more economical.

- Measures for which there is a price difference (i.e. which lie towards the centre of the graph to the left and right of the y-axis). Here, instruments that overcome this price difference (such as the CO_2 levy or emissions trading price) would be advantageous, or perhaps existing instruments need to be adapted. For example, in the case of BECCS only a "neutral" effect is currently taken into account in Swiss emissions trading, but no negative emissions.
- Measures that are still at the beginning of their learning curve and do not yet show any scaling have considerable additional costs and are on the far right of the x-axis. These are dependent on major (state) support. This could also be due to a lack of infrastructure (e.g. CO_g pipeline), so that support could also be provided in the coordination and provision of this infrastructure. Government intervention in the form of guarantees to reduce the investment risk or policies that support further innovation (e.g. subsidies) are also suitable.

However, this form of presentation also has the major **disadvantage** that it does not take into account possible overlaps between the measures. The overall potential is overestimated because, for example, the available biomass is shown several times, both in the potential for biochar and for BECCS. It is therefore necessary in a next step to calculate scenarios that avoid this double counting by making clear allocations and thus only using the available biomass once.

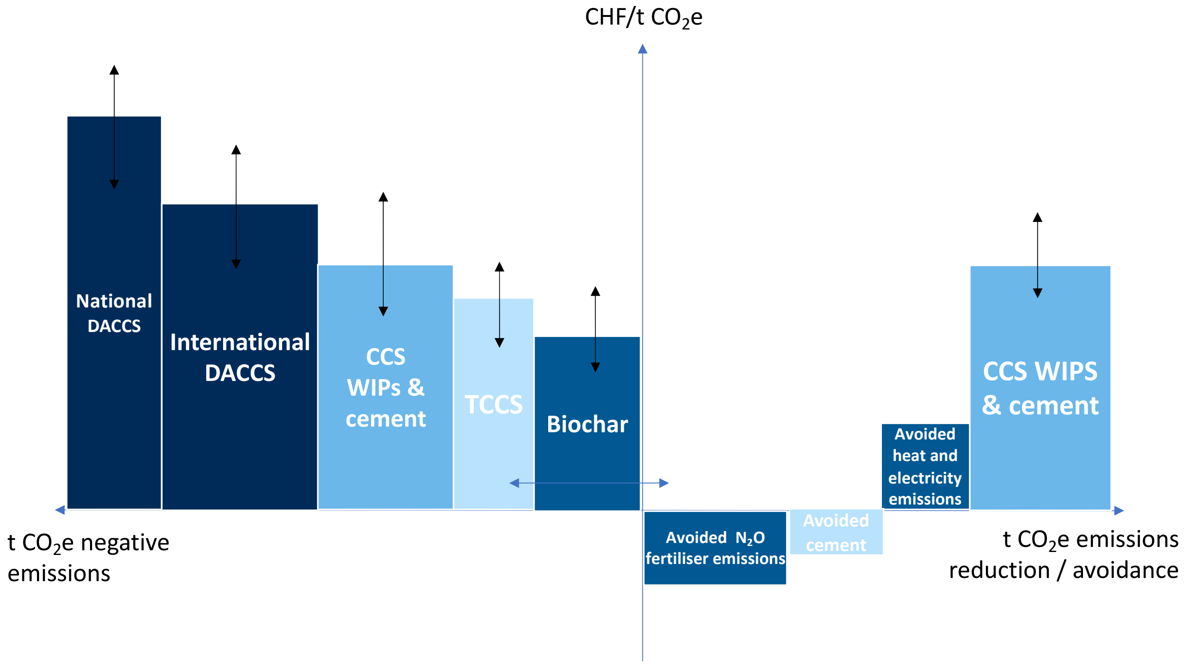

Figure 47: Sketch of a CO_2 Removal Cost Curve

4.2 Outlook on policy mixes

The above analysis shows that there are major differences in the attitudes of the various stakeholders towards policy instruments. For example, with regard to the question of whether mandatory targets are desirable, which is supported by regulators, suppliers and other actors, but not by emitters. Certain measures such as voluntary or mandatory tradable certificates for CO_2 removal, contracts for the provision of negative emissions at a guaranteed price or tax credits do not seem to be as popular, which could also be due to the fact that they are not as well understood by the CCUS community. In particular, the various standards and methodologies being developed at international, European and national levels for carbon trading will be closely monitored by DeCIRRA going forward. This includes the question of how additionality is defined in these standards, especially in the case of crediting (sub-)sectoral cumulative results instead of individual projects.

The literature review and the interactions with stakeholders in the field of CCUS and NETs in particular reveal three key regulatory and policy gaps that stand in the way of scaling:

1. Security of revenue from the fulfilment of the public good of climate protection
2. Clarity of the distribution of tasks between the federal government, cantons and the private sector
3. Clear rules for the consistent quantification and attribution of CO_2 removal or emission reductions across sectors and countries.

Point 1. seems to stand in the way of capital-intensive approaches based on the capture, transport and storage of CO_2 worldwide to date, as in the absence of a robust carbon market with very predictable and sufficiently high CO_2 prices, only state subsidies, guarantees or regulatory constraints are effective. Point 2. becomes problematic when it comes to the development of cooperative large-scale projects, such as the development of CO_2 pipelines that connect domestic CO_2 sources of various kinds with foreign means of transport. Point 3. can pose a further challenge to the two previous points in that a common understanding of ownership structures and financial flows is a prerequisite for a clear division of tasks and income security.

Therefore, as a next step, more details on possible policy instruments as well as future policy mixes to support the CCUS in Switzerland will be developed within DeCIRRA. The process and the criteria to evaluate the policy instruments or policy mixes is explained below.

The applicability of a policy instrument will be differentiated according to the level of maturity of the technology they will be applied to. Newer technologies typically need targeted support for pilot and demonstration projects, while more mature technologies require support in becoming competitive in comparison to other mitigation technologies. Over time, such support will decrease as economies of scale are achieved. We follow the Federal Council's roadmap for upscaling the uptake of CCUS technologies in assuming that up to 2030 mainly policies to support early demonstration and deployment will be needed, while from then onwards a shift towards policies to scale up deployment and increase competitiveness will be necessary.[69]

We will apply the following criteria, that have been derived from Honegger et al. (2021, 2022) for the assessment:

- **Effectiveness** refers to the ability of the policy instrument or regulation to achieve its intended goal (plus any unanticipated side benefits) (Nagel 1986), in this case, to promote the deployment of CCUS, but ultimately, to meet the net-zero emissions goal by 2050. Effectiveness can depend on various design elements of a policy. For example, in the absence of other policies, carbon prices will only be able to incentivize the uptake of CCUS if they are high enough to cover their abatement costs.
- **Efficiency** refers to the ability of the policy instrument or regulation to achieve its goal in a cost-effective (i.e., maximum result for any given financial input) manner. It can be assessed either in terms of total costs, or in terms of cost-benefit ratios (Nagel 1986). Efficiency is ideally assessed from a dynamic optimization perspective, taking into account feedbacks with the broader economy. In this report, efficiency will be assessed only in a qualitative way.
- **Distribution of costs**: Who bears the costs (and benefits) arising from the introduction of different policies and regulations is a crucial question that determines its fairness and political acceptability. Subsidies, tax rebates and other supportive policies are usually covered from government budgets, so that in the end all taxpayers bear the costs. Policies that put a price on carbon, on the contrary, directly impose costs on the producers of emissions-intensive goods, which then pass these costs on to their consumers.
- **Political feasibility**: Due to Switzerland's direct democratic system, any policy needs a broad support across political parties, relevant stakeholders and the public to be feasible. Past

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[69] https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/co2-capture-removal-storage.html

experience shows that policies that appear to create additional burdens on society – particularly taxes and levies – tend to be opposed by the population, while more supportive-looking policies – such as subsidies – enjoy broader acceptability. While this is an important criterion, it will be assessed in a later study by means of a public opinion survey about a selection of policy measures.

- **Coherence with existing Swiss and applicable international regulatory frameworks**: Switzerland already has several climate-related laws and instruments in place, including its CO_2 levy on thermal fuels (natural gas and heating oil), the ETS for large emitting installations, and the CO_2 compensation for vehicle fuel importers. In addition, the Swiss ETS is linked to the EU ETS, and their regulatory frameworks are therefore closely coordinated, particularly in terms of which types of installations may participate, and which kinds of units may be traded. Finally, Switzerland is Party to the Paris Agreement, so that the regulations concerning cooperative arrangements under Article 6 of the Paris Agreement are applicable to CCUS projects involving the cooperation between Switzerland and other countries. This criterion will be used only in the assessment of policies deployed in other countries.
- **Level of technological specificity**: There is a debate regarding the potential effect of deployment policies on inducing new forms of technological lock-in, which may carry the risk of locking out technologies that could become superior (more effective and/or efficient) in the longer term (T. S. Schmidt et al. 2016). Policies that are more technology-specific (i.e., that are designed to support a particular type of technology) are more likely to lead to such lock-ins. On the other hand, however, such targeted support may be required to support learning in less mature technologies. Generally, however, a certain level of technological diversity is desirable for a more resilient system and to be able to respond to unanticipated negative impacts of individual technologies.
- **Risks of leakage and double counting**: Leakage and double counting are specific risks related to climate policy. In this context, leakage refers to the displacement of emissions or emitting activities to places outside the coverage of a particular policy, such as a carbon tax or an emissions trading system. If emitting sources are moved to other countries, instead of actually reducing (or capturing) emissions through technical means, then no real reduction has taken place (Kreibich and Hermwille 2016). Double counting refers to the risk that emission reduction or removal units may be counted towards the fulfilment of more than one emissions reduction target of obligation (Schneider et al. 2019). Particularly in transboundary activities, where CO_2 is captured in one country and transported to a different one for storage, regulations need to clarify which side actually owns the corresponding removals.
- **Flexibility to address future uncertainty**: Given insufficient knowledge about how fast NETs will achieve cost reductions, how strongly carbon prices may rise, or whether new mitigation technologies may emerge, support policies need to be designed in a flexible way to react to changing future circumstances. For example, once certain technologies reach market maturity and become competitive at given carbon prices, more targeted support may be reduced or discontinued.

Future work under the project will apply modelling tools to quantitatively assess the distributional effects of a selected subset of policies, will develop business models for the promotion of particular CCUS options in specific economic sectors, and will use a representative survey to assess the acceptability of such policies and technologies among the Swiss population. For this reason, this policy screening is just a first step towards a more comprehensive assessment of optimal policy mixes for the deployment of CCUS options in Switzerland.

4.3 Outlook on accounting rules

The aim of SP3 of the DeCIRRA project is to answer the questions: 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 CCUS and NET in Switzerland taking into account double counting and non-permanence risks as well as uncertainties with regard to leakage? In the previous chapters the state of existing accounting rules for the different technologies has been assessed, however, there were several gaps and challenges identified which will need further analysis in the future.

A number of conceptual challenges are plaguing the proper quantification of expected results and the actual tracking thereof. 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 of 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.

One of the most significant gaps in the accounting of carbon dioxide removal results from activities involving biomass utilization and carbon capture and storage (CCS) is the lack of conceptual clarity concerning where results are achieved. There is an ongoing confusion regarding the delineation between **national greenhouse gas (GHG) inventory accounting and project-based activities**. This becomes especially complex when considering the proposal of crediting sub-pool carbon accumulation in harvested wood products (HWP) like timber. While national inventories are designed to reflect a country's overall emissions and removals, project-based accounting is generally more granular, focusing on individual projects' contributions to GHG mitigation. This dichotomy creates challenges in creating a cohesive and universally accepted accounting framework, and is often subject to inconsistencies and interpretative flexibility. Therefore, a systematic assessment of the risks or opportunities due to those different levels of accounting needs to be part of the future DeCIRRA work.

Using biochar as an example the following questions will need to be answered: How will the accounting on the national GHG inventory differ compared to project-based activities traded under Article 6.4 (compliance markets), the Swiss regulations or on the voluntary markets? Will there be a difference depending

1. on the input for the biochar production (e.g., wood is based on harvested wood products),
2. on national or cross-border sourcing of input (e.g., which methods are used in other countries)
3. on the usage of the biochar (e.g., in soils, in building material, for feedstock)?

One related question is "Who owns the achieved removal benefits of the HWP if compliance markets such as Senkeschweiz in Switzerland and the voluntary market coexist? How can substitution effects (e.g., timber construction is substitution cement or steel) be accounted for without leading to double counting (as steel and cement are covered by a cap and trade scheme)?

Another significant obstacle is the absence of clear methodologies for **assessing upstream emissions associated with forest management and the carbon content of wood products, considering potential land-use displacement effects**. The carbon content of wood products is a key parameter that needs to be accurately accounted for, as it can vary based on the management practices employed during harvesting and the subsequent land-use changes that may occur as a result. Without a robust methodology for upstream emissions and land-use impacts, it's challenging to definitively say whether a particular biomass-based project is truly contributing to climate change mitigation or inadvertently exacerbating the problem. Additionally, there is an emerging but still underdeveloped methodology for crediting emissions reduction effects from using wood products as substitutes for high-emitting products, such as in construction. Some progress is being made in this area with the development of Verified Carbon Standard (VCS) methodologies, but these are still in nascent stages.

Third, there is an overarching issue of lack of clarity on what should be quantified: the **expected mitigation result ex-ante**, or the actual mitigation result based on **measurements ex-post** or during the project operation. Forecasting mitigation results ex-ante allows for planning and adjustments but may lead to over- or under-estimation of the project's impacts. On the other hand, ex-post or ongoing measurement-based accounting provides more accurate data but might be resource-intensive and offer less flexibility for adjustments. This dichotomy adds another layer of complexity to an already intricate landscape, making the standardization and harmonization of accounting practices a challenging endeavor.

The question of ex-ante and ex-post is also closely linked to the question of the duration of **crediting periods or the definition of "permanence" for removal projects or if a better wording would be "temporary storage times"**. The Swiss law does require 30 years in Art. 5.2 of the CO_2-ordinance for carbon removals such as biochar, but the IPCC 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) applies a 100-year time frame because biochar is more persistent. An understanding of the implications of different carbon storage durations for biochar and harvested wood products would be important as it may have impact on prices on removal credits and therefore DeCIRRA will look into this topic.

5 References

Albicker, M., Eichler, M., Flöer, L., Hader, P., & Zwankhuizen, A. (2023). *Carbon Capture & Storage (CCS) – Kostenschätzung für ein CCS-System für die Schweiz bis 2050*. Basel: BAK Economics AG und Deutsche Energieagentur. https://www.bafu.admin.ch/dam/bafu/de/dokumente/klima/externe-studien-berichte/kostenschaetzung-fuer-ein-ccs-system-fuer-die-schweiz-bis-2050.pdf. Accessed 6 December 2023

Amiri, A., Ottelin, J., Sorvari, J., & Junnila, S. (2020). Cities as carbon sinks—classification of wooden buildings. *Environmental Research Letters*, *15*(9), 094076. https://doi.org/10.1088/1748-9326/aba134

Antonini, C., Treyer, K., Moioli, E., Bauer, C., Schildhauer, T. J., & Mazzotti, M. (2021). Hydrogen from wood gasification with CCS – a techno-environmental analysis of production and use as transport fuel. *Sustainable Energy & Fuels*, *5*(10), 2602–2621. https://doi.org/10.1039/D0SE01637C

Antonini, C., Treyer, K., Streb, A., Spek, M. van der, Bauer, C., & Mazzotti, M. (2020). Hydrogen production from natural gas and biomethane with carbon capture and storage – A techno-environmental analysis. *Sustainable Energy & Fuels*, *4*(6), 2967–2986. https://doi.org/10.1039/D0SE00222D

Athias, L., Macina, M., & Wicht, P. (2019). Public-Private Partnerships: A Swiss Perspective. In A. Ladner, N. Soguel, Y. Emery, S. Weerts, & S. Nahrath (Eds.), *Swiss Public Administration: Making the State Work Successfully* (pp. 187–204). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-92381-9_11

Bader, P. (2022). Wald und Boden: Mit Bäumen das Klima schützen. *Die Umwelt*, *2/2022*, 36–38. https://www.bafu.admin.ch/bafu/de/home/themen/klima/dossiers/magazin-2022-2-dossier/wald-und-boden-mit-baeumen-das-klima-schuetzen.html. Accessed 27 October 2023

Becattini, V., Gabrielli, P., Antonini, C., Campos, J., Acquilino, A., Sansavini, G., & Mazzotti, M. (2022). Carbon dioxide capture, transport and storage supply chains: Optimal economic and environmental performance of infrastructure rollout. *International Journal of Greenhouse Gas Control*, *117*, 103635. https://doi.org/10.1016/j.ijggc.2022.103635

Bellamy, R., & Geden, O. (2019). Govern CO2 removal from the ground up. *Nature Geoscience*, *12*(11), 874–876. https://doi.org/10.1038/s41561-019-0475-7

Beuttler, C., Keel, S. G., Leifeld, J., Schmid, M., Berta, N., Gutknecht, V., et al. (2019). *The Role of Atmospheric Carbon Dioxide Removal in Swiss Climate Policy – Fundamentals and Recommended Actions.* Bern: Risk Dialogue Foundation. Commissioned by the Federal Office for the Environment, Bern. https://www.aramis.admin.ch/Default?DocumentID=61230&Load=true. Accessed 21 February 2022

Brander, M., Ascui, F., Scott, V., & Tett, S. (2021). Carbon accounting for negative emissions technologies. *Climate Policy*, *21*(5), 699–717. https://doi.org/10.1080/14693062.2021.1878009

Brunner, C., & Knutti, R. (2022). *Potenziale und Kosten der CO_2-Entfernung aus der Atmosphäre in der Schweiz*. Zurich: ETH Zürich. https://www.bafu.admin.ch/bafu/de/home/themen/thema-klima/klima--publikationen-und-studien/klima--studien.html. Accessed 1 November 2023

Bundesamt für Umwelt (BAFU). (2021). *Totalrevision der Verordnung über die Verminderung von Treibhausgasemissionen (CO_2-Verordnung): Erläuternder Bericht* (p. 132). Bern, Switzerland: Bundesamt für Umwelt.

Bundesamt für Umwelt (BAFU). (2022). *Jahrbuch Wald und Holz 2022* (No. UZ-2225-D) (p. 108). Bern, Switzerland: Bundesamt für Umwelt. https://www.bafu.admin.ch/dam/bafu/de/dokumente/wald-holz/uz-umwelt-zustand/jahrbuch-wald-und-holz-2022.pdf.download.pdf/UZ-2225-D_JB-WaldHolz%202022.pdf

Bundesamt für Umwelt (BAFU), Bundesamt für Landwirtschaft (BLW), & Arbeitsgruppe Interventionswerte und Risikobeurteilung (AGIR) des Cercle Sol. (2023). *Pflanzenkohle in der Schweizer Landwirtschaft - Risiken und Chancen für Boden und Klima* (Faktenblatt). Bern, Switzerland: Bundesamt für Umwelt. https://www.bafu.admin.ch/dam/bafu/de/dokumente/klima/fachinfo-daten/faktenblatt-pflanzenkohle-2022.pdf.download.pdf/D_Faktenblatt_Pflanzenkohle.pdf. Accessed 26 October 2023

Bundesrat. Verordnung vom 30. November 2012 über die Reduktion der CO_2-Emissionen. , Pub. L. No. SR 641.711 (2012). https://www.fedlex.admin.ch/eli/cc/2012/856/de. Accessed 26 October 2023

Bundesrat. (2020). *Von welcher Bedeutung könnten negative CO_2-Emissionen für die künftigen klimapolitischen Massnahmen der Schweiz sein? Bericht des Bundesrates in Erfüllung des Postulates 18.4211 Thorens Goumaz vom 12. Dezember 2018*. Bern, Switzerland: Der Bundesrat, Schweizerische Eidgenossenschaft. https://www.newsd.admin.ch/newsd/message/attachments/62745.pdf. Accessed 25 October 2023

Bundesrat. (2022). *CO_2-Abscheidung und Speicherung (CCS) und Negativemissionstechnologien (NET): Wie sie schrittweise zum langfristigen Klimaziel beitragen können. Bericht des Bundesrates*. Bern, Switzerland: Der Bundesrat, Schweizerische Eidgenossenschaft. https://www.newsd.admin.ch/newsd/message/attachments/71551.pdf. Accessed 25 October 2023

Bundesrat. (2023). *Kohlenstoffsequestrierung in Böden. Bericht des Bundesrats in Erfüllung des Postulats 19.3639 Bourgeois vom 18. Juni 2019*. Bern, Switzerland: Der Bundesrat, Schweizerische Eidgenossenschaft. https://www.newsd.admin.ch/newsd/message/attachments/76407.pdf. Accessed 26 October 2023

Cafaggi, S. (2022, June 16). *Challenges and Opportunities for Biochar and Mass Timber Constructions as NETs in Switzerland* (M.Sc. thesis). ZHAW School of Management and Law, Winterthur.

Calvin, K., Cowie, A., Berndes, G., Arneth, A., Cherubini, F., Portugal-Pereira, J., et al. (2021). Bioenergy for climate change mitigation: Scale and sustainability. *GCB Bioenergy*, *13*(9), 1346–1371. https://doi.org/10.1111/gcbb.12863

Cames, M., Mader, C., Hermann, A., Köhler, A. R., Malinverno, N., Möller, M., et al. (2023). *Chancen und Risiken von Methoden zur Entnahme und Speicherung von CO2 aus der Atmosphäre: Empfehlungen aufgrund der Analyse des Wissensstandes und einer systematischen Befragung von Fachleuten in der Schweiz*. (TA-SWISS, Ed.) (1st ed.). Zurich: vdf Hochschulverlag AG an der ETH Zürich. https://doi.org/10.3218/4153-8

Cemsuisse. (2021). *Roadmap 2050: Klimaneutraler Zement als Ziel*. Bern: Cemsuisse. https://www.cemsuisse.ch/app/uploads/2021/04/Cemsuisse_Roadmap_210422.pdf. Accessed 30 October 2023

Chevalier, G., Diamond, L. W., & Leu, W. (2010). Potential for deep geological sequestration of CO2 in Switzerland: a first appraisal. *Swiss Journal of Geosciences*, *103*(3), 427–455. https://doi.org/10.1007/s00015-010-0030-4

Churkina, G., Organschi, A., Reyer, C. P. O., Ruff, A., Vinke, K., Liu, Z., et al. (2020). Buildings as a global carbon sink. *Nature Sustainability*, *3*(4), 269–276. https://doi.org/10.1038/s41893-019-0462-4

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., et al. (2014). Carbon and Other Biogeochemical Cycles. In Intergovernmental Panel On Climate Change, T. F. Stocker, D. Qin, G.-K. Plattner, M. M. B. Tignor, S. K. Allen, et al. (Eds.), *Climate Change 2013 – The Physical Science Basis* (1st ed., pp. 465–570). Cambridge, United Kingdom: Cambridge University Press. https://doi.org/10.1017/CBO9781107415324.015

Clarke, L., Wei, Y.-M., De La Vega Navarro, A., Garg, A., Hahmann, A. N., Khennas, S., et al. (2023). Energy Systems. In P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, et al. (Eds.), *Climate Change 2022 - Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1st ed., pp. 613–746). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157926.008

Cleveland, M. (2017). *Carbon Capture and Sequestration* (Policy Paper). Denver, CO: National Conference of State Legislatures. https://www.wyoleg.gov/Interimcommittee/2017/09-0629appendixg-1.pdf. Accessed 24 August 2023

Cobo, S., Galán-Martín, Á., Tulus, V., Huijbregts, M. A. J., & Guillén-Gosálbez, G. (2022). Human and planetary health implications of negative emissions technologies. *Nature Communications*, *13*(1), 2535. https://doi.org/10.1038/s41467-022-30136-7

Cobo, S., Negri, V., Valente, A., Reiner, D. M., Hamelin, L., Dowell, N. M., & Guillén-Gosálbez, G. (2023). Sustainable scale-up of negative emissions technologies and practices: where to focus. *Environmental Research Letters*, *18*(2), 023001. https://doi.org/10.1088/1748-9326/acacb3

Cooper, L., & MacFarlane, D. (2023). Climate-Smart Forestry: Promise and risks for forests, society, and climate. *PLOS Climate*, *2*(6), e0000212. https://doi.org/10.1371/journal.pclm.0000212

Cordier, S., Blanchet, P., Robichaud, F., & Amor, B. (2022). Dynamic LCA of the increased use of wood in buildings and its consequences: Integration of CO_2 sequestration and material substitutions. *Building and Environment*, *226*, 109695. https://doi.org/10.1016/j.buildenv.2022.109695

Cowie, A., Pingoud, K., & Schlamadinger, B. (2006). Stock changes or fluxes? Resolving terminological confusion in the debate on land-use change and forestry. *Climate Policy*, *6*(2), 161–179. https://doi.org/10.1080/14693062.2006.9685593

Creutzig, F., Ravindranath, N. H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., et al. (2015). Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy*, *7*(5), 916–944. https://doi.org/10.1111/gcbb.12205

de Kleijne, K., Hanssen, S. V., van Dinteren, L., Huijbregts, M. A. J., van Zelm, R., & de Coninck, H. (2022). Limits to Paris compatibility of CO_2 capture and utilization. *One Earth*, *5*(2), 168–185. https://doi.org/10.1016/j.oneear.2022.01.006

Deutz, S., & Bardow, A. (2021). Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. *Nature Energy*, *6*(2), 203–213. https://doi.org/10.1038/s41560-020-00771-9

Diamond, L. W. (2019). *Deep underground heat reservoirs, Joint NRP70 project "Hydropower and geoenergy"* (Technical Report). Bern: University of Bern. https://nfp-energie.ch/en/projects/960/. Accessed 2 November 2023

Dittli, L. (2023, June 15). *Negativemissionstechnologien: Schweizer Akteur Netzwerk und die Einstellung zu Politiken* (M.Sc. thesis). ZHAW School of Management and Law, Winterthur.

Driesner, T., Gischig, V., Hertrich, M., Loew, S., Maurer, H., Mazzotti, M., et al. (2021). *Swiss Potential for Geothermal Energy and CO_2 Storage: Synthesis Report* (Report). Zurich: ETH Zurich. https://doi.org/10.3929/ethz-b-000518184

Eggelston, S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (Eds.). (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Kanagawa: Institute for Global Environmental Strategies (IGES). https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html. Accessed 25 October 2023

Elkerbout, M., & Bryhn, J. (2019). *An enabling framework for carbon capture and storage (CCS) in Europe: A overview of key issues* (CEPS Policy Brief No. 2019/03). Brussels: Centre for European Policy Studies. https://www.ceps.eu/wp-content/uploads/2019/09/RB2019_03_An-enabling-framework-for-carbon-capture-and-storage-in-Europe.pdf. Accessed 1 November 2023

European Union. Regulation (EU) 2022/869 of the European Parliament and of the Council of 30 May 2022, on guidelines for trans-European energy infrastructure. , Pub. L. No. 2022/869 (2022). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022R0869. Accessed 1 November 2023

Fajardy, M., & Dowell, N. M. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? *Energy & Environmental Science*, *10*(6), 1389–1426. https://doi.org/10.1039/C7EE00465F

Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO_2 direct air capture plants. *Journal of Cleaner Production*, *224*, 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086

Finch, H. (2022). An introduction to the analysis of ranked response data. *Practical Assessment, Research, and Evaluation*, *27*(7). https://doi.org/10.7275/TGKH-QK47

Frattini, L., Becattini, V., Krüger, M., Akeret, O., & Mazzotti, M. (2022, August 30). Legal and Regulatory Gaps for Carbon Dioxide Capture, Transport, and Storage Deployment. SSRN Scholarly Paper, Rochester, NY. https://doi.org/10.2139/ssrn.4285233

Frischknecht, R., Althaus, H.-J., Bauer, C., Doka, G., Heck, T., Jungbluth, N., et al. (2007). The Environmental Relevance of Capital Goods in Life Cycle Assessments of Products and Services. *The International Journal of Life Cycle Assessment*, *12*, 7–17. https://doi.org/10.1065/lca2007.02.309

Frischknecht, R., & Pfäffi, K. (2023). *Bilanzierung von Negativemissionen (NET) im Bauwesen*. Zürich: Stadt Zürich, Amt für Hochbauten. https://www.stadt-zuerich.ch/content/dam/stzh/hbd/Deutsch/Hochbau/Weitere%20Dokumente/Bauen-2000-Watt/Grundlagen-Studienergebnisse/NB/2023/2023-03-nb-Bilanzierung-Negative-Emissionen-Bauwesen.pdf. Accessed 27 October 2023

Frischknecht, R., & Ramseier, L. (2020). *Broschüre Ökobilanzen Holz und Holzgebäude*. Uster: treeze Ltd. https://treeze.ch/fileadmin/user_upload/downloads/Publications/Case_Studies/Building_and_Construction/631_Broschuere_Holzrechner.pdf. Accessed 27 October 2023

Fuhrman, J., Bergero, C., Weber, M., Monteith, S., Wang, F. M., Clarens, A. F., et al. (2023). Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. *Nature Climate Change*, *13*(4), 341–350. https://doi.org/10.1038/s41558-023-01604-9

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., et al. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

Gauch, M., Matasci, C., Hincapié, I., Hörler, R., & Böni, H. (2016). *Material- und Energieressourcen sowie Umweltauswirkungen der baulichen Infrastruktur der Schweiz* (No. 21033) (p. 79). St. Gallen: Empa - Materials Science & Technology. https://www.dora.lib4ri.ch/empa/islandora/object/empa%3A15590/. Accessed 27 October 2023

Gea-Bermúdez, J., Jensen, I. G., Münster, M., Koivisto, M., Kirkerud, J. G., Chen, Y., & Ravn, H. (2021). The role of sector coupling in the green transition: A least-cost energy system development in Northern-central Europe towards 2050. *Applied Energy*, *289*, 116685. https://doi.org/10.1016/j.apenergy.2021.116685

Geng, A., Yang, H., Chen, J., & Hong, Y. (2017). Review of carbon storage function of harvested wood products and the potential of wood substitution in greenhouse gas mitigation. *Forest Policy and Economics*, *85*, 192–200. https://doi.org/10.1016/j.forpol.2017.08.007

Goglio, P., Williams, A. G., Balta-Ozkan, N., Harris, N. R. P., Williamson, P., Huisingh, D., et al. (2020). Advances and challenges of life cycle assessment (LCA) of greenhouse gas removal technologies to fight climate changes. *Journal of Cleaner Production*, *244*, 118896. https://doi.org/10.1016/j.jclepro.2019.118896

Grubb, M., Hourcade, J. C., & Neuhoff, K. (2013). *Planetary economics: energy, climate change and the three domains of sustainable development*. New York: Routledge.

Gustavsson, L., & Sathre, R. (2011). Energy and CO_2 analysis of wood substitution in construction. *Climatic Change*, *105*(1), 129–153. https://doi.org/10.1007/s10584-010-9876-8

Hasegawa, T., Fujimori, S., Frank, S., Humpenöder, F., Bertram, C., Després, J., et al. (2021). Land-based implications of early climate actions without global net-negative emissions. *Nature Sustainability*, *4*(12), 1052–1059. https://doi.org/10.1038/s41893-021-00772-w

Haubold-Rosar, M., Heinkele, T., Rademacher, A., Kern, J., Dicke, C., Funke, A., et al. (2016). *Chancen und Risiken des Einsatzes von Biokohle und anderer „veränderter“ Biomasse als Bodenhilfsstoffe oder für die C-Sequestrierung in Böden* (Texte No. 04/2016) (p. 254). Dessau-Roßlau: Umweltbundesamt. https://www.umweltbundesamt.de/publikationen/chancen-risiken-des-einsatzes-von-biokohle-anderer. Accessed 26 October 2023

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (Eds.). (2018). *Life Cycle Assessment: Theory and Practice*. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3

Himes, A., & Busby, G. (2020). Wood buildings as a climate solution. *Developments in the Built Environment*, *4*, 100030. https://doi.org/10.1016/j.dibe.2020.100030

Hofer, P., Taverna, R., Werner, F., Kaufmann, E., & Thürig, E. (2007). *CO_2-Effekte der Schweizer Wald- und Holzwirtschaft* (No. UW-0739-D) (p. 102). Bern, Switzerland: Bundesamt für Umwelt. https://www.bafu.admin.ch/bafu/de/home/themen/klima/publikationen-studien/publikationen/co2-effekte-schweizer-wald-holzwirtschaft.html. Accessed 27 October 2023

Holzer, K. (2021). The Pending EU CBAM: *Quo Vadis* Switzerland? *Global Trade and Customs Journal*, *16*(11/12), 633–643. https://doi.org/10.54648/GTCJ2021080

Honegger, M., Baatz, C., Eberenz, S., Holland-Cunz, A., Michaelowa, A., Pokorny, B., et al. (2022). The ABC of Governance Principles for Carbon Dioxide Removal Policy. *Frontiers in Climate*, *4*. https://doi.org/10.3389/fclim.2022.884163

Honegger, M., Poralla, M., Michaelowa, A., & Ahonen, H.-M. (2021). Who Is Paying for Carbon Dioxide Removal? Designing Policy Instruments for Mobilizing Negative Emissions Technologies. *Frontiers in Climate*, *3*. https://doi.org/10.3389/fclim.2021.672996

Intergovernmental Panel on Climate Change (IPCC). (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change*. (B. Metz, O. Davidson, H. de Coninck, M. Loos, & L. Meyer, Eds.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf

Intergovernmental Panel on Climate Change (IPCC). (2006). Glossary. In S. Eggelston, L. Buendia, K. Miwa, T. Ngara, & K. Tanabe (Eds.), *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Kanagawa: Institute for Global Environmental Strategies (IGES). https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html. Accessed 25 October 2023

Intergovernmental Panel on Climate Change (IPCC). (2014). *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol*. (T. Hiraishi, T. Krug, K. Tanabe, N. Srivastava, J. Baasansuren, M. Fukuda, & T. Troxler, Eds.). Geneva, Switzerland: IPCC. https://www.ipcc.ch/site/assets/uploads/2018/03/KP_Supplement_Entire_Report.pdf. Accessed 27 October 2023

Intergovernmental Panel on Climate Change (IPCC). (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. (E. Calvo Buendía, K. Tanabe, A. Kranjc, J. Baasansuren, M. Fukuda, S. Ngarize, et al., Eds.). Geneva, Switzerland: IPCC. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html. Accessed 27 October 2023

Intergovernmental Panel on Climate Change (IPCC). (2023). Annex I: Glossary. In P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, et al. (Eds.), *Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1793–1820). Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157926.020

International Energy Agency. (2022). *Direct Air Capture: A key technology for net zero*. Paris: Organisation for Economic Co-operation and Development. https://doi.org/10.1787/bbd20707-en

Jakob, B. (2022). Die wichtigsten NET-Ansätze. *Die Umwelt*, *2/2022*, 13–15. bafu.admin.ch/magazin2022-2-02. Accessed 27 October 2023

Kannan, R., & Turton, H. (2014). *Switzerland energy transition scenarios – Development and application of the Swiss TIMES Energy system Model (STEM)* (PSI Bericht No. 14– 06). Villigen: Paul Scherrer Institut (PSI). https://www.psi.ch/sites/default/files/import/eem/PublicationsTabelle/2014-STEM-PSI-Bericht-14-06.pdf

Kayo, C., Kalt, G., Tsunetsugu, Y., Hashimoto, S., Komata, H., Noda, R., & Oka, H. (2021). The default methods in the 2019 Refinement drastically reduce estimates of global carbon sinks of harvested wood products. *Carbon Balance and Management*, *16*(1), 37. https://doi.org/10.1186/s13021-021-00200-8

Kemmler, A., Lübbers, S., Ess, F., Thormeyer, C., & Althaus, H.-J. (2021). *Energieperspektiven 2050+: Exkurs Negativemissionstechnologien und CCS - Potenziale, Kosten und Einsatz* (Energieperspektiven 2050+). Bern, Switzerland: Bundesamt für Energie. https://www.bfe.admin.ch/bfe/de/home/politik/energieperspektiven-2050-plus.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGljYX/Rpb24vZG93bmxvYWQvMTA2MjA=.html. Accessed 30 October 2023

Kemper, J. (2015). Biomass and carbon dioxide capture and storage: A review. *International Journal of Greenhouse Gas Control*, *40*, 401–430. https://doi.org/10.1016/j.ijggc.2015.06.012

Kreibich, N., & Hermwille, L. (2016). *Robust Transfers of Mitigation Outcomes - Understanding Environmental Integrity Challenges* (Policy Paper). Wuppertal: Wuppertal Institute for Climate, Environment and Energy.

https://epub.wupperinst.org/frontdoor/deliver/index/docId/6496/file/6496_Robust_Transfers.pdf. Accessed 23 August 2023

Lädrach, T. (2022). *Jahresbericht 2022 Holzindustrie Schweiz*. Bern: Holzindustrie Schweiz. https://www.holz-bois.ch/fileadmin/his/Dokumente/Jahresbericht/Jahresbericht_2022_Holzindustrie_Schweiz_D.pdf. Accessed 27 October 2023

Lamster, J. (2023). *Ökologische Kennzahlen für Investoren: Vergleich Holzbau Massivbau*. Zürich: durable Planung und Beratung GmbH. https://www.aramis.admin.ch/Default?DocumentID=70545&Load=true. Accessed 27 October 2023

Lin, X., Li, W., Guo, Y., Dong, W., Castel, A., & Wang, K. (2023). Biochar-cement concrete toward decarbonisation and sustainability for construction: Characteristic, performance and perspective. *Journal of Cleaner Production*, *419*, 138219. https://doi.org/10.1016/j.jclepro.2023.138219

Matthews, H. D. (2010). Can carbon cycle geoengineering be a useful complement to ambitious climate mitigation? *Carbon Management*, *1*(1), 135–144. https://doi.org/10.4155/cmt.10.14

McQueen, N., Psarras, Peter. C., Pilorgé, H., Liguori, S., He, J., Yuan, M., et al. (2020). Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the U.S. *Environmental Science & Technology*, *54*(12), 7542–7551. https://doi.org/10.1021/acs.est.0c00476

Mehli, A., Gerner, G., Kulli Honauer, B., Baier, U., Kühni, M., Treichler, A., et al. (2021). *HTC Innovationscampus Rheinmühle - Pilotanlage zur hydrothermalen Karbonisierung: Prozessoptimierung & Verfahrenserkenntnisse (Schlussbericht)* (Schlussbericht). Bern: Bundesamt für Energie. https://doi.org/10.21256/zhaw-21929

Michaelowa, A., Honegger, M., Poralla, M., Winkler, M., Dalfiume, S., & Nayak, A. (2023). International carbon markets for carbon dioxide removal. *PLOS Climate*, *2*(5), e0000118. https://doi.org/10.1371/journal.pclm.0000118

Moioli, E., & Schildhauer, T. (2022). Negative CO_2 emissions from flexible biofuel synthesis: Concepts, potentials, technologies. *Renewable and Sustainable Energy Reviews*, *158*, 112120. https://doi.org/10.1016/j.rser.2022.112120

Müller, D., Eichenberger, M., & Stenz, M. (2015). *Holzbau vs. Massivbau – Ein umfassender Vergleich zweier Bauweisen im Zusammenhang mit dem SNBS-Standard*. Rain: PIRMIN JUNG Schweiz AG. https://www.bafu.admin.ch/dam/bafu/de/dokumente/wald-holz/fachinfo-daten/holzbau_vs_massivbaueinumfassendervergleichzweierbauweisenimzusa.pdf.download.pdf/holzbau_vs_massivbaueinumfassendervergleichzweierbauweisenimzusa.pdf. Accessed 27 October 2023

Müller, D., & Moser, D. (2022). *Rückbau und Wiederverwendung von Holzbauten*. Rain: PIRMIN JUNG Schweiz AG.

Nabuurs, G.-J., Mrabet, R., Abu Hatab, A., Bustamante, M., Clark, H., Havlík, P., et al. (2023). Agriculture, Forestry and Other Land Uses (AFOLU). In P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, et al. (Eds.), *Climate Change 2022 - Mitigation of Climate Change* (1st ed., pp. 747–860). Cambridge University Press. https://doi.org/10.1017/9781009157926.009

Nagel, S. S. (1986). Efficiency, Effectiveness, and Equity in Public Policy Evaluation. *Review of Policy Research*, *6*(1), 99–120. https://doi.org/10.1111/j.1541-1338.1986.tb00651.x

Nakhle, C., Eckle, P., & Krüger, M. (2022). *Decarbonizing Cement: Technology assessment and policy relevant evidence for the decarbonization of the Swiss cement industry* (Final report). Zurich: ETH Zurich. https://www.aramis.admin.ch/Default?DocumentID=69298&Load=true. Accessed 30 October 2023

Neele, F., Mikunda, T., Seebregts, A., Santen, S., van der Burgt, A., Stiff, S., & Hustad, C. (2013). A Roadmap Towards a European CO2 Transport Infrastructure. *Energy Procedia*, *37*, 7774–7782. https://doi.org/10.1016/j.egypro.2013.06.724

Neerup, R., Løge, I. A., Helgason, K., Snæbjörnsdóttir, S. Ó., Sigfússon, B., Svendsen, J. B., et al. (2022). A Call for Standards in the CO_2 Value Chain. *Environmental Science & Technology*, *56*(24), 17502–17505. https://doi.org/10.1021/acs.est.2c08119

Nick, S., & Thalmann, P. (2021). *Carbon removal, net zero, and implications for Switzerland* (E4S White Paper No. 2021–5). Lausanne: Enterprise for Society Center. https://e4s.center/wp-content/uploads/2022/09/CCUS_WhitePaper-EN.pdf. Accessed 30 October 2023

Nussbaum, C. (2023). Stand zu den Speicheroptionen in der Schweiz. Presented at the Energieforschungsgespräche Disentis 2023, Disentis: Fachhochschule Graubünden und Alpenforce.

Panos, E., Kannan, R., Hirschberg, S., & Kober, T. (2022). *Net-zero CO_2 emissions scenarios for Switzerland* (preprint). In Review. https://doi.org/10.21203/rs.3.rs-1874405/v1

Panos, E., Kannan, R., Hirschberg, S., & Kober, T. (2023). An assessment of energy system transformation pathways to achieve net-zero carbon dioxide emissions in Switzerland. *Communications Earth & Environment*, *4*(1), 1–18. https://doi.org/10.1038/s43247-023-00813-6

Panos, E., Kober, T., Ramachandran, K., Hirschberg, S., Bauer, C., Schildhauer, T., et al. (2021). *Transformation of the Swiss Energy System for a Net-Zero Greenhouse Gas Emission Society: Results from the Joint Activity Scenarios & Modelling* (Report). Zurich: ETH Zurich. https://doi.org/10.3929/ethz-b-000518179

Pape, C., Budaragina, M., Honegger, M., Poralla, M., & Winkler, M. (2023). *Strategy paper: Enabling CCUS value chains for Swiss climate neutrality* (Strategy paper). Zurich: Southpole Carbon and Perspectives Climate Research.

Petersson, H., Ellison, D., Appiah Mensah, A., Berndes, G., Egnell, G., Lundblad, M., et al. (2022). On the role of forests and the forest sector for climate change mitigation in Sweden. *GCB Bioenergy*, *14*(7), 793–813. https://doi.org/10.1111/gcbb.12943

Pittau, F., Habert, G., Savi, D., & Klingler, M. (2022). *Carbon storage project: Technical report: Methodology for biogenic carbon accounting and carbonation in LCA of buildings and construction products* (Report). Zürich: Stadt Zürich, Amt für Hochbauten. https://doi.org/10.3929/ethz-b-000554234

Poralla, M., Honegger, M., Gameros, C., Wang, Y., Sacherer, A.-K., Ahonen, H.-M., et al. (2022). *Tracking greenhouse gas removals: Baseline and monitoring methodologies, additionality, testing, and accounting*. London and Freiburg i. B.: NET-Rapido Consortium and Perspectives Climate Research. https://doi.org/10.5167/uzh-230035

Pourhashem, G., Hung, S. Y., Medlock, K. B., & Masiello, C. A. (2019). Policy support for biochar: Review and recommendations. *GCB Bioenergy*, *11*(2), 364–380. https://doi.org/10.1111/gcbb.12582

Qiu, Y., Lamers, P., Daioglou, V., McQueen, N., de Boer, H.-S., Harmsen, M., et al. (2022). Environmental trade-offs of direct air capture technologies in climate change mitigation toward 2100. *Nature Communications*, *13*(1), 3635. https://doi.org/10.1038/s41467-022-31146-1

Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., et al. (2017). The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews*, *68*, 333–359. https://doi.org/10.1016/j.rser.2016.09.107

Rey, L., & Thalmann, P. (2017). *Holzbeschaffung und nachhaltige Holznutzung* (p. 36). Bern: Schweizerischer Nationalfonds. https://www.nfp66.ch/media/de/U9FR1kW1bWK1fNS9/NFP66_Teilsynthese_4_Holzbeschaf_DE.pdf. Accessed 27 October 2023

Rickels, W., Proelß, A., Geden, O., Burhenne, J., & Fridahl, M. (2020). *The future of (negative) emissions trading in the European Union* (Working Paper No. No. 2164). Kiel: Kiel Institute for the World Economy.

Röhrdanz, M., Pannemann, F., Dittrich, K., Klenke, T., Buchwald, R., & Wark, M. (2019). Erweiterung der Verwertungs-Kaskaden von Reststoff-Biomassen durch die Herstellung von HTC-Biokohle am Beispiel unterschiedlicher Güllearten. In J. Marx Gómez, A. Solsbach, T. Klenke, & V. Wohlgemuth (Eds.), *Smart Cities/Smart Regions – Technische, wirtschaftliche und gesellschaftliche Innovationen* (pp. 755–763). Wiesbaden: Springer Fachmedien. https://doi.org/10.1007/978-3-658-25210-6_58

Rüter, S., Matthews, R. W., Lundblad, M., Sato, A., & Hassan, R. A. (2019). Chapter 12: Harvested Wood Products. In E. Calvo Buendía, K. Tanabe, A. Kranjc, J. Baasansuren, M. Fukuda, S. Ngarize, et al. (Eds.), *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse*

Gas Inventories (Vol. 4). Geneva, Switzerland: IPCC. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html. Accessed 27 October 2023

Rystad, J. (2022). The role of CCS in Europe's decarbonisation. Presented at the Northern Lights Summit 2022, Rystad Energy. https://norlights.com/news/join-us-at-the-northern-lights-summit-2022/. Accessed 6 December 2023

SAIPEM. (2020). *CO2NET – Grobes Design und Kostenschätzung für ein CO_2 Sammel-Netzwerk in der Schweiz*. Milano: SAIPEM. https://www.aramis.admin.ch/Texte/?ProjectID=47346. Accessed 30 October 2023

Savi, D., & Klingler, M. (2022). *Kohlenstoffspeicherung im Holzbau: Potenzial des Gebäudeparks in der Schweiz: Schlussbericht* (Report). Zurich: Stadt Zürich, Amt für Hochbauten, Fachstelle nachhaltiges Bauen. https://www.stadt-zuerich.ch/content/dam/stzh/hbd/Deutsch/Hochbau/Weitere%20Dokumente/Bauen-2000-Watt/Grundlagen-Studienergebnisse/NB/2022/2022-05-nb-Kohlenstoffspeicherung-im-Holzbau-Schlussbericht.pdf. Accessed 27 October 2023

Schmidt, H.-P., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T. D., Monedero, M. A. S., & Cayuela, M. L. (2021). Biochar in agriculture – A systematic review of 26 global meta-analyses. *GCB Bioenergy*, *13*(11), 1708–1730. https://onlinelibrary.wiley.com/doi/abs/10.1111/gcbb.12889. Accessed 31 May 2023

Schmidt, T. S., Battke, B., Grosspietsch, D., & Hoffmann, V. H. (2016). Do deployment policies pick technologies by (not) picking applications?—A simulation of investment decisions in technologies with multiple applications. *Research Policy*, *45*(10), 1965–1983. https://doi.org/10.1016/j.respol.2016.07.001

Schneider, L., Duan, M., Stavins, R., Kizzier, K., Broekhoff, D., Jotzo, F., et al. (2019). Double counting and the Paris Agreement rulebook. *Science*, *366*(6462), 180–183. https://doi.org/10.1126/science.aay8750

Schweizerische Eidgenossenschaft. Bundesgesetz über die Ziele im Klimaschutz, die Innovation und die Stärkung der Energiesicherheit (KlG). , Pub. L. No. BBI 2022 2403 (2022). https://www.fedlex.admin.ch/eli/fga/2022/2403/de. Accessed 25 October 2023

Selberherr, J., Meier, S., & Kunz, M. (2020). *Holzbaukennzahlen für Investoren*. Zürich: Wüest Partner AG. https://www.bafu.admin.ch/dam/bafu/de/dokumente/wald-holz/fachinfo-daten/Holzbaukennzahlen_Schlussbericht_200813.pdf.download.pdf/Holzbaukennzahlen_Schlussbericht_200813.pdf. Accessed 27 October 2023

Selberherr, J., Pöschik, M., & Habegger, R. (2022). *Holzbaukennzahlen für Investoren – Bürobauten*. Zürich: Wüest Partner AG. https://www.lignum.ch/files/images/Downloads_deutsch/Holzbaukennzahlen_Buerobauten_WP_Lignum_BAFU.pdf

Shayegh, S., Bosetti, V., & Tavoni, M. (2021). Future Prospects of Direct Air Capture Technologies: Insights From an Expert Elicitation Survey. *Frontiers in Climate*, *3*. https://doi.org/10.3389/fclim.2021.630893

Singhal, S. (2023). Biochar as a cost-effective and eco-friendly substitute for binder in concrete: a review. *European Journal of Environmental and Civil Engineering*, *27*(2), 984–1009. https://doi.org/10.1080/19648189.2022.2068658

Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., et al. (2019). Land-Management Options for Greenhouse Gas Removal and Their Impacts on Ecosystem Services and the Sustainable Development Goals. *Annual Review of Environment and Resources*, *44*(1), 255–286. https://doi.org/10.1146/annurev-environ-101718-033129

Smith, S., Geden, O., Nemet, G., Gidden, M., Lamb, W., Powis, C., et al. (2023). *State of Carbon Dioxide Removal - 1st Edition*. Open Science Framework. https://doi.org/10.17605/OSF.IO/W3B4Z

Sovacool, B. K., Baum, C. M., Low, S., Roberts, C., & Steinhauser, J. (2022). Climate policy for a net-zero future: ten recommendations for Direct Air Capture. *Environmental Research Letters*, *17*(7), 074014. https://doi.org/10.1088/1748-9326/ac77a4

Strefler, J., Bauer, N., Humpenöder, F., Klein, D., Popp, A., & Kriegler, E. (2021). Carbon dioxide removal technologies are not born equal. *Environmental Research Letters*, *16*(7), 074021. https://doi.org/10.1088/1748-9326/ac0a11

Suter, F. (2016). *To use or not to use: Environmental effects of wood utilization in Switzerland* (Doctoral Thesis). ETH Zürich, Zürich. Retrieved from https://www.research-collection.ethz.ch/handle/20.500.11850/121744

Tanase, L., & Herrera Anchustegui, I. (2023, April 27). EU Hydrogen and the Decarbonized Gas Market Package: Unbundling, Third-Party Access, Tariffs and Discounts Rules at the Core of Transport of Hydrogen. SSRN Scholarly Paper, Rochester, NY. https://doi.org/10.2139/ssrn.4431113

Tanner, C. (2022, June 16). *Carbon Capture Storage (CCS) and Utilization (CCU) for Switzerland's Path to Net Zero* (M.Sc. thesis). ZHAW School of Management and Law, Winterthur.

Tanzer, S. E., & Ramírez, A. (2019). When are negative emissions negative emissions? *Energy & Environmental Science*, *12*(4), 1210–1218. https://doi.org/10.1039/C8EE03338B

Terlouw, T., Bauer, C., Rosa, L., & Mazzotti, M. (2021). Life cycle assessment of carbon dioxide removal technologies: a critical review. *Energy & Environmental Science*, *14*(4), 1701–1721. https://doi.org/10.1039/D0EE03757E

Terlouw, T., Treyer, K., Bauer, C., & Mazzotti, M. (2021). Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources. *Environmental Science & Technology*, *55*(16), 11397–11411. https://doi.org/10.1021/acs.est.1c03263

Teske, S. L., Rüdisüli, M., Bach, C., & Schildhauer, T. (2019). *Potentialanalyse Power-to-Gas in der Schweiz. Betrachtungen zu Technologien, CO_2, Standorten, Elektrizität, Wirtschaftlichkeit und Einsatz in der Mobilität*. Dübendorf and Villigen: EMPA and PSI. https://doi.org/10.5281/zenodo.2649817

Thees, O., Burg, V., Erni, M., Bowman, G., & Lemm, R. (2017). *Biomassepotenziale der Schweiz für die energetische Nutzung. Ergebnisse des Schweizerischen Energiekompetenzzentrums SCCER BIOSWEET* (No. Heft 57, 2017) (p. 299). Birmensdorf: Eidgenossische Forschungsanstalt für Wald, Schnee und Landschaft (WSL). https://www.dora.lib4ri.ch/wsl/islandora/object/wsl%3A13277/. Accessed 31 May 2023

Think Wood. (2021). *Understanding the Role of Embodied Carbon in Climate Smart Buildings: Report on Carbon Reduction Policy and Design Best Practices*. Think Wood.

UNFCCC. (2003). *Estimation, Reporting and Accounting of Harvested Wood Products* (Technical Paper No. FCCC/TP/2003/7). Bonn: UNFCCC Secretariat. http://unfccc.int/resource/docs/tp/tp0307.pdf. Accessed 25 October 2023

UNFCCC. (2022). *Concept note: Removal activities under the Article 6.4 Mechanism. Version 01.0* (No. A6.4-SB001-AA-A05). Bonn: UNFCCC Secretariat. https://unfccc.int/sites/default/files/resource/a64-sb001-aa-a05.pdf. Accessed 27 October 2023

UNFCCC. (2023). *Draft recommendation: Activities involving removals under the Article 6.4 mechanism. Version 03.0* (No. A6.4-SB008-AA-A15). Bonn: UNFCCC Secretariat. https://unfccc.int/sites/default/files/resource/a64-sb008-aa-a15.pdf. Accessed 31 October 2023

United Nations Economic Commission for Europe (UNECE) (Ed.). (2018). *European Agreement concerning the international carriage of dangerous goods by inland waterways: (ADN) including the annexed regulations, applicable as from 1 January 2019. Volume 2*. Presented at the Diplomatic Conference for the Adoption of a European Agreement Concerning the International Carriage of Dangerous Goods by Inland Waterways, New York and Geneva: United Nations. https://unece.org/DAM/trans/danger/publi/adn/ADN2019/ADN_2019_E_Web.pdf. Accessed 1 November 2023

van den Broek, M., Mesquita, P., Carneiro, J., Silva, J. R., Berghout, N., Ramírez, A., et al. (2013). Region Specific Challenges of a CO_2 Pipeline Infrastructure in the West Mediterranean Area Model Results Versus Stakeholder Views. *Energy Procedia*, *37*, 3137–3146. https://doi.org/10.1016/j.egypro.2013.06.200

Verband der Betreiber Schweizerischer Abfallverwertungsanlagen (VBSA). (2023). *Bericht 2022 zur Vereinbarung zwischen UVEK und VBSA betreffend der Reduktion der fossilen CO_2-Emissionen aus der Abfallverbrennung und Umsetzung von Technologien zur Abscheidung, Speicherung und Nutzung von CO_2 in Schweizer Kehrichtverwertungsanlagen.* Bern: VBSA. https://www.bafu.admin.ch/dam/bafu/de/dokumente/klima/fachinfo-daten/VBSA-CO2-Report_2023_Def.pdf. Accessed 10 October 2023

Verkerk, P. J., Costanza, R., Hetemäki, L., Kubiszewski, I., Leskinen, P., Nabuurs, G. J., et al. (2020). Climate-Smart Forestry: the missing link. *Forest Policy and Economics*, *115*, 102164. https://doi.org/10.1016/j.forpol.2020.102164

Vilarrasa, V. (2016). The role of the stress regime on microseismicity induced by overpressure and cooling in geologic carbon storage. *Geofluids*, *16*(5), 941–953. https://doi.org/10.1111/gfl.12197

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Winterberg, N., Weber, R., Laggner, L., & Näher, T. (2022). *Holzendverbrauch Schweiz 2019/20*. Biel: Berner Fachhochschule, Institut für digitale Bau- unud Hozwirtschaft IdBH. https://www.bfh.ch/dam/jcr:07039fa4-a9cd-4e64-b9ab-48423cfeb20a/gesamtbericht-bafu-holzendverbrauch-ch-2019-2020.pdf. Accessed 27 October 2023

Withey, P., Johnston, C., & Guo, J. (2019). Quantifying the global warming potential of carbon dioxide emissions from bioenergy with carbon capture and storage. *Renewable and Sustainable Energy Reviews*, *115*, 109408. https://doi.org/10.1016/j.rser.2019.109408

Xiang, L., Liu, S., Ye, S., Yang, H., Song, B., Qin, F., et al. (2021). Potential hazards of biochar: The negative environmental impacts of biochar applications. *Journal of Hazardous Materials*, *420*, 126611. https://doi.org/10.1016/j.jhazmat.2021.126611

Ziaja, J., Wisniowski, R., Jamrozik, A., & Knez, D. (2018). Modern Construction Technologies of Gas Pipelines and Oil Pipelines. Presented at the 18th International Multidisciplinary Scientific GeoConference SGEM2018, Albena, Bulgaria. https://doi.org/10.5593/sgem2018/1.4/S06.080

6 Appendix

Table 17: 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. Ausweitung des Schweizer Technologiefonds zu einem Schweizer Carbon Removal Fonds Schaffung von Anreizen für den Einsatz von CO_2-Entnahme-Technologien durch eine markante Erhöhung des Preises für Klik-Zertifikate Defizitgarantien für first movers Garantien setzen für die Grossinvestitionen insb. für gemeinsame Infrastruktur-Bedarfe, die sonst nicht getätigt werden. Vergünstigte Elektrizitätspreise für Verflüssigung von CO_2 Anschubfinanzierung für CO_2 Logistikkette (z.B. Bahnverladeanlagen) 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. CCS soll auch durch den Verursacher bezahlt werden. 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) Weitere Anreize (Steuerliche Anreize, Unterstützende Lenkungsmassnahmen, Unterstützung von freiwilligen Aktivitäten im Bereich CDR)	3 1 1 1 1 1 1 1 1 1 3
Creation of infrastructure and networks	Ausbau von CO_2-Transportinfrastrukturen Schaffung einer Organisation aus Behörden und Privatunternehmen zur Koordination und Umsetzung von CO_2-Entnahme-Massnahmen Einrichtung von CCS/CCU/CDR-Hubs und Clustern Massiver Ausbau an erneuerbaren Energien und Projekte, welche die Infrastruktur für deren Verteilung garantieren. Erarbeitung von Business Modellen für alle verschiedenen Emittentengruppen	3 3 1 1 1
International cooperation and agreements	Abschluss von internationalen Verträgen zur Regelung des Transports und der Speicherung von abgefangenem CO_2 Klärung und Beseitigung regulatorischer Hemmnisse für den internationalen Transport und Handel mit CO_2-Entnahme (Zoll, Deklaration Abfall/Chemical) Artikel 6-Pilotprojekte Schweizer CDR Technologieanbieter im Ausland	4 2 1
Communication and awareness creation	Informationskampagnen, um die Bedeutung von CO_2-Entnahme-Massnahmen der breiten Bevölkerung näherzubringen Förderung von Fachverbänden und Wissensplattformen zur Schaffung von Austausch und Zusammenarbeit	2 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 18: 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
	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 importierte Produkte.	1
	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.) 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 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. 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. 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. 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. Die konsequente Verknüpfung mit einer Kreislaufwirtschaft, mit besonderem Blick auf die Nutzung von Biochar im Kreislauf, statt Erdölprodukte Anpassung des Waldes an den Klimawandel	5 1 1 1 1 1

Table 19: 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) Suche/Kartografieren von möglichen Speicherstätten in der Schweiz Unterzeichnung bilateraler Abkommen mit Ländern mit geologischem Speicherpotenzial (Norwegen, Dänemark, Niederlande); Besprechung konkreter Liefer- und Abnahmemengen Rechtsgrundlage für die Entwicklung einer Pipeline schaffen / Eine CO_2 Pipeline muss auf Bundesebene koordiniert werden. Verwaltung des Untergrunds ist offensichtlich Sache der Kantone. Rechtlicher Rahmen für Liability für den Fall von Leakage / Seepage (inkl. Versicherungsmodi + private-public partnerships um Risiken zu reduzieren) 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). Planungstechnische Schritte zur inländischen Speicherung (Untergrund und Produkte) unternehmen (inkl. öffentlicher Debatte).	16 9 8 4 2 2 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