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Potentials and costs of CO_2 removal in Switzerland

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Illustration on the cover page:
Horgen waste incineration plant (own illustration), which is being equipped with a carbon capture unit with subsequent sequestration of the CO_2 as part of the Airfix project. Net operation of the plant will remove CO_2 from the atmosphere.

Abstract

Carbon dioxide removal (CDR) from the atmosphere is an unavoidable element in achieving net zero CO_2 or greenhouse gas emissions. This commissioned study estimates the technical potential as well as the costs of the CDR methods afforestation, reforestation and improved forest management (IFM), bioenergy with carbon capture and storage (BECCS), soil carbon sequestration (SCS), sequestration of biochar, enhanced silicate rock weathering (ERW), and direct air capture and storage (DACS) in Switzerland. Possibilities and costs for the transport and the storage of CO_2 in Switzerland and abroad are also estimated. Existing scientific literature as well as publications of Swiss federal agencies serve as a basis for the synthesis.

The technical CDR potential in Switzerland without DACS is estimated at 30 $MtCO_2$-eq/year. For DACS, no potential estimate was found in the scientific literature. The potential for geological storage in Switzerland is still insufficiently assessed. The present estimate of the technical CDR potential is significantly higher than in previous estimates, primarily because ERW, biomass already used for energy, and timber harvesting are now included in this estimate. Due to several limiting factors, the actual achievable potential for CDR in Switzerland is likely to be significantly smaller than the technical potential mentioned. However, the environmental and economic constraints do not fundamentally query a substantial contribution of CDR within Switzerland to achieving the net zero target. Furthermore, how much CDR will effectively be utilized in Switzerland in the future depends on the political-economic framework, climate policy, abatement costs of greenhouse gas emissions, and the support and involvement of the population.

The estimated costs vary widely, from about -40 to 930 CHF/tCO_2-eq, and depend on the particular CDR method. While for some, currently rather expensive CDR methods, costs are expected to decrease due to economies of scale, the costs of currently rather cheaper CDR methods are expected to increase in the future, due to saturation effects and a scarcity of resources.

Introduction

Carbon Dioxide Removal is “unavoidable” to bring anthropogenic CO_2 or greenhouse gas emissions to net zero (IPCC, 2022). CDR methods are "anthropogenic activities that remove CO_2 from the atmosphere and store it permanently in geological, terrestrial, or oceanic reservoirs or in products" (IPCC, 2022). What storage duration "permanently" corresponds to has not yet been adequately clarified scientifically. Initial work indicates that the storage duration must be greater than 300 years (e.g., Matthews, 2010). CDR is not a substitute for emission reduction, but an essential component of a climate strategy for the mitigation of human-induced climate change (IPCC, 2022).

In order to make its contribution to reaching the climate targets set out in the Paris Agreement, the Swiss Federal Council wants Switzerland to achieve a greenhouse gas balance of net zero by 2050. In its long-term climate strategy of January 2021, it presented guidelines to achieve this net zero target. Based on the Energy Perspectives 2050+ (Kemmler et al., 2021a), the “Langfristige Klimastrategie” shows how greenhouse gas emissions within Switzerland can reach net zero by 2050. The same is envisaged by the Federal Law on Climate Protection Targets, Innovation and Strengthening Energy Security (the indirect counter-proposal to the Glacier Initiative), which was passed by the Swiss Parliament on 30.9.2022. It defines, in addition to reduction targets during the years 2030-2050 and the net zero interim target in 2050, net negative greenhouse gas emissions after 2050 in order to contribute to lowering the global mean temperature back to below 1.5°C after a potential overshoot. The definition of the extent to which CDR should play a role in the Swiss climate policy is of crucial importance so that Swiss politics, industry as well as research and society can position themselves accordingly and set the necessary framework today, also because there could be potential conflicts in the use of limited resources such as biomass. The Swiss Federal Council shows in a recent report how carbon capture and storage (CCS) and negative emission technologies can gradually contribute to Switzerland's long-term climate goal (Federal Council, 2022). In doing so, the Federal Council envisions the removal of about 7 $MtCO_2$/year to balance the residual emissions that are hard to avoid in 2050.

This report was commissioned by the Federal Office for the Environment (FOEN). Within the scope of the mandate, it quantifies the potentials and costs for CDR methods in Switzerland on the basis of existing scientific literature as well as publications of the Swiss federal offices.

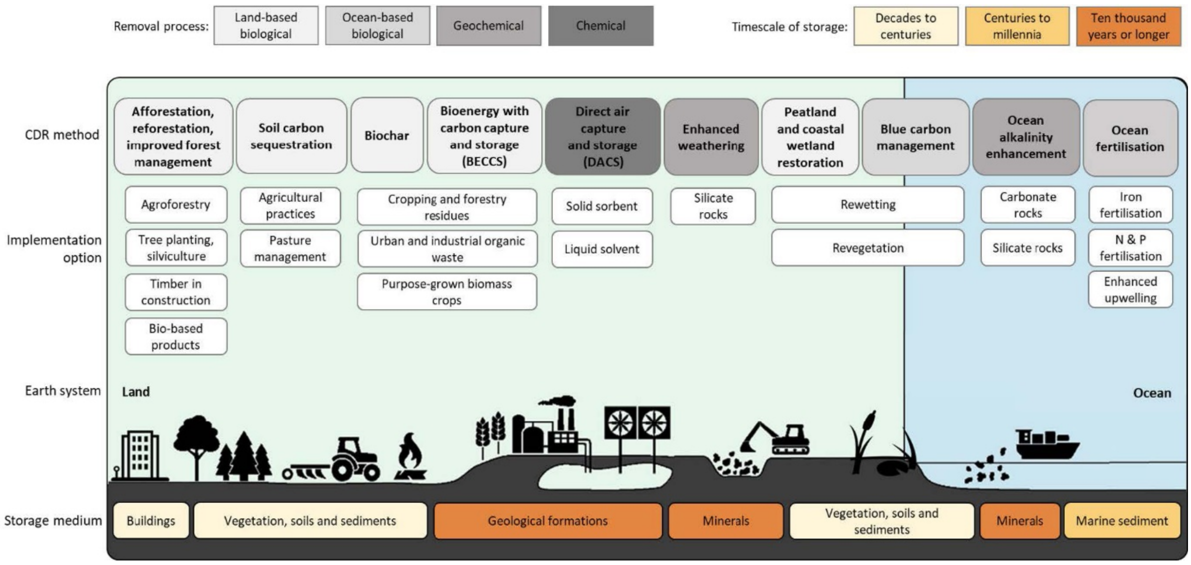

Fig. 1: CDR taxonomy. Source: IPCC (2022) based on Minx et al. (2018).

Figure 1 shows a common classification of different CDR methods, on which removal process they are based (land-based biological, ocean-based biological, geochemical or chemical) as well as how long the removed CO_2 remains stored. Not all methods can be applied in Switzerland, for example due to lack of access to an ocean. This study addresses the CDR methods relevant for Switzerland: afforestation, reforestation and improved forest management, bioenergy with carbon capture and storage, soil carbon sequestration, sequestration of biochar, enhanced silicate rock weathering, and direct air capture and storage. The various CDR methods are briefly presented below, and their potentials and costs are estimated. In some CDR methods, gaseous or liquid CO_2 is captured and must be sequestered (= stored). The different storage options, their potentials and costs as well as the transport of CO_2 are discussed following the CDR methods.

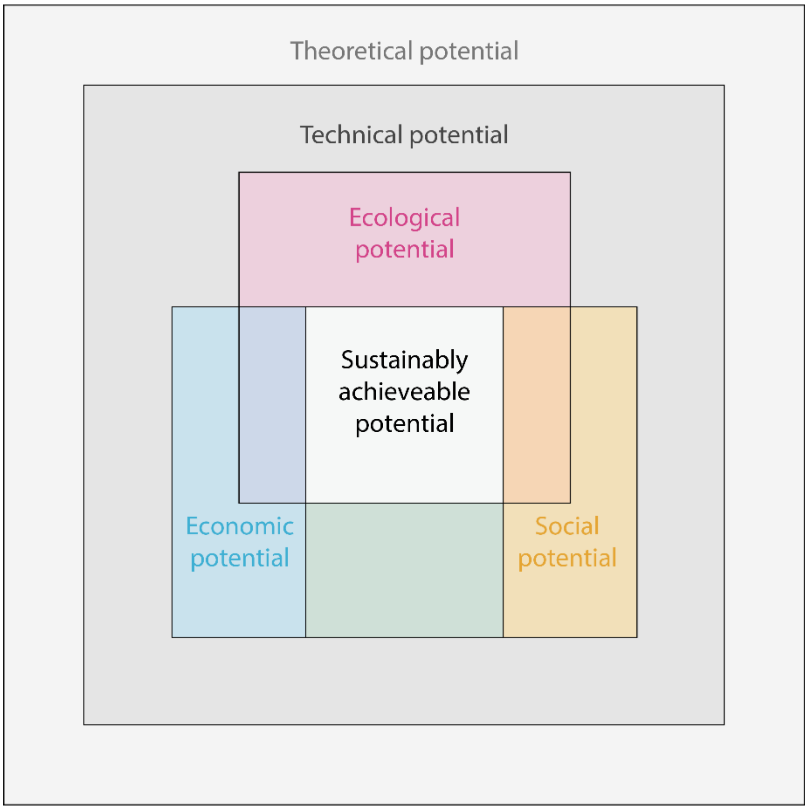

Fig. 2: Classification of the various potentials. Graphic based on Federal Council (2020).

The focus of this study is on the technical potential, which is, depending on the CDR method, supplemented by economic and ecological aspects. The technical potential quantifies the amount that can be achieved "within the limits of physics and chemistry" and "according to the current state of research" (Bundesrat, 2020). Relevant for the actual implementation is the sustainably achievable potential (see Fig. 2; Federal Council, 2020), which forms a subset of the technical potential. The quantified potentials do not include greenhouse gas emissions that would occur during the realization of the potentials. Nor do they provide any information on the indirect reductions of other greenhouse gas emissions as a result of utilizing a CDR method, for example because of substitution effects.

Potentials and costs of CDR methods in Switzerland

Afforestation, Reforestation and Improved Forest Management

Through photosynthesis, vegetation in the Swiss forest as well as in the landscape removes CO_2 from the atmosphere and stores it in the woody biomass. The amount removed can be increased by afforestation, reforestation as well as by improved forest management. As long as the vegetation remains intact, or harvested woody biomass is not burned or otherwise decomposed, CO_2 storage persists, typically for decades to centuries in long-lived wood products.

Due to the dynamics of the carbon cycle or the reversible CO_2 fertilization effect, only the CO_2 uptake of the Swiss forest that is additionally caused by intentional human actions is a CDR method (see definition of CDR in the introduction). For example, the CO_2 uptake of a pristine forest would not be a CDR method from a natural science perspective. In the case of forest management, as is the case for most forests in Switzerland, only the difference of the real CO_2 uptake of the managed area to a baseline is eligible (IPCC, 2022). The baseline quantifies the CO_2 uptake that would occur if the managed forest area had remained untouched.

CDR potential

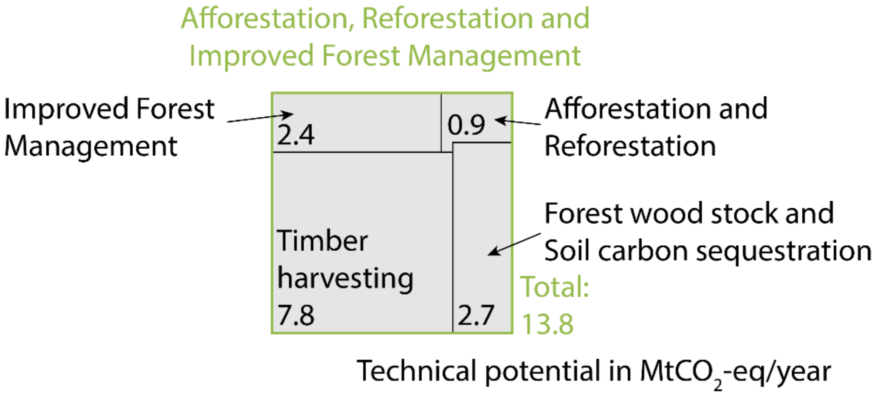

Fig. 3: The estimated technical potentials of afforestation, reforestation, and improved forest management in $MtCO_2$-eq/year.

The technical CDR potential of afforestation, reforestation, and improved forest management in Switzerland is estimated at 13.8 $MtCO_2$/year and is composed of four sub-potentials (see Fig. 3).
For afforestation or reforestation in Switzerland, the technical CDR potential is estimated at 0.87 $MtCO_2$/year (Austin et al 2020; Roe et al, 2021). This requires land use change away from pasture and cropland, and more dense settlement and with less sealed surfaces.

For the estimation of the further sub-potentials in the Swiss forest, a baseline remains missing that quantifies what CO_2 uptake the Swiss forest would have if it had remained untouched. As a first approximation, therefore, only the real CO_2 uptake of the Swiss forest is considered in the present estimate. Since only the difference between the real CO_2 uptake and the baseline would be eligible as CDR, the present approximation probably leads to an overestimation of the actual technical CDR potential.

The Swiss forest removed an average of 12.9 $MtCO_2$-eq/year in the period 2010-2019 (FOEN, 2021a). According to simulations with a forest development model, this amount can be temporarily increased by 2.4 $MtCO_2$-eq/year to 15.3 $MtCO_2$-eq/year through improved forest management (Taverna et al., 2007). After subtracting natural removals, harvesting, and logging residue, the remaining increment contributes to forest stock buildup or depletion in the forest. In this context, the forest stock represents a carbon stock. The leftover biomass is also an input of carbon to forest soils. In the period 2010-2019, the mean CO_2 balance[1] from CO_2 losses and CO_2 uptake in the Swiss forest was 2.7 $MtCO_2$-eq/year (FOEN, 2021a). The technical potential for timber harvesting in Switzerland varies depending on forest management and is estimated to be up to 8.5 million m^3 of rough wood when demand for wood is high (Stadelmann et al., 2016), which corresponds to about 7.8 $MtCO_2$-eq/year.[2] Through a distinct cascade use, for example in building construction, wood products or paper/cardboard, the previously removed CO_2 can remain stored during material utilization. Following material utilization, the woody biomass should therefore be used as feedstock for bioenergy with carbon capture and storage as well as for the production of biochar, so that the CO_2 remains stored over climate-relevant periods of time.

Due to various influencing factors, it can be assumed that the realizable potential of afforestation, reforestation and improved forest management is lower than the quantified technical potential for the following reasons:

- The baseline discussed above is missing for the Swiss forest so far.
- A land use change in favor of additional forest areas leads to conflicting social goals.
- Timber harvesting leads to a constant removal of nutrients from the forest. Leaving logging residues in the forest reduces nutrient loss, since most nutrients are in the branches, foliage and bark. However, the loss is not stopped. A nutrient deficit can have a detrimental effect on ecosystems as well as on the growth of vegetation in the forest.
- The realization of timber harvesting potential in mountainous terrain is complex and correspondingly more cost-intensive than timber harvesting in the Swiss plateau. In the short and medium term, timber harvesting in mountainous terrain also generates more greenhouse gas emissions than in the Swiss plateau. The greenhouse gas emissions generated during the utilization of a CDR method were not quantified in the present study.
- Energy wood as well as waste wood after a cascade use would have to be used energetically in such a way that the CO_2 stored in the woody biomass remains permanently stored in another form. In the case of small furnaces, such as fireplaces or pellet heating systems, this is technically hardly possible in the foreseeable future. Consequently, to realize the maximum potential, small furnaces should no longer be operated. In the case of medium-sized furnaces, such as combined heat and power plants, the production and sequestration of biochar offers a possibility of storing the CO_2 absorbed by the biomass for a longer period of time in some cases (see below). This would have the consequence that only a corresponding proportion of the

[1] "The CO_2 balance of the forest is composed of CO_2 uptake as a result of tree growth, changes in stored carbon in litter, soil, and deadwood minus losses as a result of forest use and natural removals (dead trees)" (FOEN, 2021b).

[2] Simplified assumption based on Taverna et al. (2007): 1 m^3 of rough wood weighs approx. 0.5 t, of which 50% is carbon. Thus, 1 m^3 of rough wood stores approx. 0.917 tCO_2.

thermal energy could be used. The economic efficiency of such plants may therefore be lower than for conventional combined heat and power plants. Larger plants would have to be consistently operated with CCS (see bioenergy with carbon capture and storage below).
- The impact of climate change on vegetation is uncertain. Prolonged drought, fires, or more frequent extreme events could deplete the wood supply in the forest.

Cost
The cost of afforestation or reforestation is estimated globally at 0-240 CHF/tCO_2-eq (Smith et al., 2016; Fuss et al., 2018). Estimated timber harvesting costs in Switzerland vary by timber use, geographic location, and time period. For the period 2027-2056, it is estimated that 4.3 million m^3 of rough wood per year (3.9 MtCO_2-eq/year) could be harvested for less than 87 CHF/tCO_2-eq, 3.4 million m^3 of rough wood per year (3.1 MtCO_2-eq/year) for 87 to 164 CHF/tCO_2-eq, and 1.4 million m^3 of rough wood per year (1.3 MtCO_2-eq/year) for more than 164 CHF/tCO_2-eq (Stadelmann et al., 2016). There are also additional costs due to forest management.

Bioenergy with carbon capture and storage

Bioenergy with carbon capture and storage (BECCS) uses woody and non-woody biomass for energy provision, while capturing and storing CO_2 from the resulting waste gases using CCS. Examples of BECCS include the combustion of organic waste in waste-to-energy plants with CCS, the upgrading of biogas with subsequent storage of the captured CO_2, the combustion of biogas or non-fossil fuels in gas-fired power plants with CCS, or the combustion of waste wood in cement plants with CCS.

CDR potential
The potential of BECCS in Switzerland depends primarily on the biomass potential for energy use and on suitable storage options for the captured CO_2. Thees et al. (2017) estimated the sustainably achievable potential for energy use from biomass in Switzerland at 97 PJ per year. The study also considered economic factors. Combustion of this biomass would release 12.0 MtCO_2/year, of which 49% would come from woody biomass (see Appendix A1 for details on the calculation). With (post-combustion) CO_2 capture plants, 90% or more can typically be achieved. Costs increase with increasing CO_2 capture rates (Brandl et al., 2021). Thus, the technical potential of BECCS would be 10.8 MtCO_2/year, of which 5.3 MtCO_2/year would come from woody biomass.

To realize the full CDR potential of BECCS, all biomass used for energy would have to be combusted in such a way that the CO_2 from the combustion is captured and remains stored durably. This would likely preclude the use of biomass as an energy feedstock in smaller facilities, such as wood or biogas in households or in vehicles. The achievable potential is reduced if smaller plants were operated without CCS and only larger plants were operated as BECCS: Rosa et al. (2021) estimated the technical potential for BECCS by retrofitting existing pulp and paper mills, wastewater treatment plants, plants with biomass firing, and waste-to-energy plants in Switzerland with CCS to be 2.0 MtCO_2/year. Plants that emitted at least 0.1 MtCO_2 in 2018 were considered. Swiss waste-to-energy plants showed a continuing trend to burn steadily more biomass: In 2010 and 2019, 31% and 50% more biomass was burned than in 2000, respectively (both based on calorific value; FOEN

2021a). In 2019, biomass combustion in Swiss waste-to-energy plants resulted in CO_2 emissions of 2.3 $MtCO_2$/year (BAFU 2021a). A comprehensive application of CCS at Swiss waste-to-energy plants would thus not only lead to CDR, but also greatly reduce CO_2 emissions from fossil waste incineration, which amounted to 2.1 $MtCO_2$/year in 2019 (BAFU 2021a). Technically, CCS application would be possible for all plants if there is sufficient space, a suitable heat source, and a way to transport or store the captured CO_2. However, as pointed out above by Rosa et al. (2021), the economics become more challenging for smaller plants. For Swiss cement plants, CCS could also greatly reduce fossil or geogenic CO_2 emissions on the one hand, and lead to CDR through the use of biomass as fuel on the other. The Swiss Cement Industry Association projects that Swiss cement plants using BECCS would lead to CDR in the range of 0.3 $MtCO_2$/year in 2050 (Cemsuisse, 2021). In general, with BECCS, the geological storage of CO_2 within Switzerland is still insufficiently clarified (see below).

Cost

The costs for BECCS vary depending on the type of bioenergy utilization plant. For Swiss waste-to-energy plants with CCS, initial costs are estimated at 156-190 CHF/tCO_2 (including transport and storage). In this context, CO_2 capture and compression excluding transport and storage is estimated to cost 45-51 CHF/tCO_2 in the initial implementation and 32-46 CHF/tCO_2 in the future (Eckle et al., 2021). In the future, biomass is expected to become a scarce resource, which may lead to an increase in costs.

Sequestration of biochar

Biochar is produced during the pyrolysis of plant biomass. Pyrolysis takes place between 450-750°C in an oxygen-deficient environment, where approximately 20-50% of the CO_2 that the biomass previously removed from the atmosphere remains stored for centuries to several millennia (e.g., Schmidt et al., 2021). Biochar can be incorporated into soils or building materials, where the carbon it contains degrades slowly. A pyrolysis plant can provide heat and, depending on the plant, electricity. However, the energy yield is lower than if the plant biomass were completely burned. A higher pyrolysis temperature generally results in more stable carbon storage. In the process, the CDR potential decreases because a smaller portion of the initial biomass carbon remains in the biochar (Lehmann et al., 2021). Correctly adjusted process parameters and a selective choice of biomass avoid a possible pollutant load of the biochar during the production of the biochar.

CDR potential

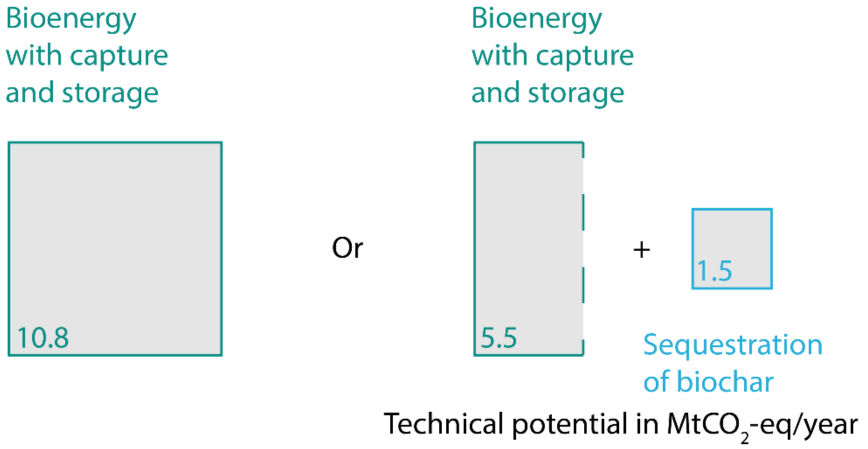

Fig. 4: BECCS and biochar production compete for the same biomass feedstock. Technical potentials in $MtCO_2$-eq/year.

Some of the same biomass as for BECCS can be used as feedstock for the production of biochar (see Fig. 4). Schmidt et al. (2021) estimated a technical CDR potential of 1.5 $MtCO_2$-eq/year for the production and sequestration of biochar in soils based on the biomass potential for energy use in Switzerland from Thees et al. (2017), which would use 49% of the sustainably available biomass. If the remaining biomass were used for BECCS, the CDR potential for BECCS would be 5.5 $MtCO_2$/yr.

Pyrolysis plants are typically smaller than plants using CCS. This makes pyrolysis plants suitable as replacements for existing conventional wood-fired power plants, for example. A possible obstacle is the lower efficiency and the consequently increased fuel demand compared to existing wood-fired power plants, since incomplete combustion of the fuel is deliberately intended. In the case of small firing systems, such as fireplaces or pellet heating systems, appropriate pyrolysis systems have been lacking up to now. If these remain missing, the maximum potential cannot be reached.

Cost

The cost of biochar sequestration (including production of the biochar) is estimated globally at 9-320 CHF/tCO_2-eq (10-345 USD/tCO_2-eq; IPCC, 2022). Cost estimates often refer to woody biomass as feedstock. Since the availability of woody biomass feedstock is more limited in Switzerland than in other countries, it can be assumed that the lower cost limit is likely to be unrealistic for the sequestration of biochar in Switzerland.

Soil Carbon Sequestration

Soil Carbon Sequestration (SCS) is a process in which a new, higher soil carbon equilibrium is established in the soil through changes in land management practices, whereby the temporary soil carbon buildup results in a net removal of CO_2 from the atmosphere. In the process, organic carbon inputs are increased and removals are reduced. This can be achieved, for example, by changing crop rotation, intercropping, deep plowing, etc. The sequestration achieved is potentially lost if the favorable land management practices are ever abandoned. It is therefore only permanent if the management practices are maintained indefinitely. Through the postulate Bourgeois (19.3639), a report on carbon sequestration in soils is currently being prepared.

CDR potential

In general, there are large uncertainties in estimates of the CDR potential of SCS, and the amount of CO_2 removed decreases over time as the difference from the new equilibrium state becomes smaller. Lee et al. (2020) quantifies, depending on the measure, that soil carbon could be built up by 0.4-1.8 tCO_2-eq/ha annually, which would correspond to a technical CDR potential of 0.17-0.77 $MtCO_2$-eq/year for SCS until the new soil carbon equilibrium is reached for all cropland in Switzerland[3]. However, this study has been criticized for too high losses in the baseline, which probably overestimates the potential (Nesme et al., 2020).

Guillaume et al. (2022) estimated for the canton of Fribourg that additional soil carbon of 0.85 MtC could be built up in arable soils with a higher proportion of temporary grassland in the rotation. In this context, it could take more than a century to reach this new equilibrium, with the greatest soil carbon buildup rates occurring at the beginning (Poeplau et al., 2011; Smith, 2014).

Based on global models, the technical potential of SCS on Swiss permanent grassland soils is estimated at 0.65 $MtCO_2$-eq/year (Soils Revealed, 2020; Roe et al., 2021).

Cost

SCS costs are estimated to range from -42 to 93 CHF/tCO_2-eq globally (-45 to 100 USD/tCO_2-eq; Smith et al., 2016; Fuss et al., 2018; NASEM, 2019).

Enhanced Silicate Rock Weathering

Calcium- and magnesium-rich silicate rocks weather and bind CO_2 in the process. Enhanced silicate rock weathering (ERW) accelerates this naturally very slow process, for example by crushing the rock to increase its surface area and then spreading it on soils.

CDR potential

The CDR potential of ERW depends on several variables, such as soil properties (e.g., pH), biological activity (fungi, bacteria, fauna, and flora), rock type and particle size, application rate, and climatic conditions (e.g., temperature and humidity). Beerling et al. (2020) estimated the technical CDR potential for croplands in Germany, France, and Italy to be the equivalent of 6.1 tCO_2/ha per year on average (4.1 and 8.0 tCO_2/ha per year for slow and fast weathering, respectively). For Swiss cropland, this would correspond[3] to a technical

[3] Areas in Switzerland (BFS, 2021): Arable land 388,383 ha; natural meadows and home pastures 512,788 ha each in the period 2013-2018. Forest land: 730,960 ha in NFI economic regions

CDR potential of 2.3 $MtCO_2$/year (1.6 and 3.1 $MtCO_2$/year for slow and fast weathering, respectively). In addition to cropland, ERW can also be applied to pastures, meadows (e.g., Groll et al., 2021; Hagens et al., 2021), and forest (e.g., Taylor et al., 2021), which are estimated to increase the technical CDR potential of ERW to approximately 10 $MtCO_2$/yr. More precise determination of the technical CDR potential of ERW requires field testing as well as specific simulations with a land surface model. It has not yet been conclusively determined whether suitable rocks for ERW occur in Switzerland.

Cost
Beerling et al. (2020) estimated globally the cost of ERW on cropland at 80-180 USD/tCO_2 (74-166 CHF/tCO_2 including transportation of rock from abroad).

Direct Air Capture and Storage

Direct Air Capture and Storage (DACS) is a CDR method for removing CO_2 directly from the atmosphere using specially designed processes and then permanently storing the CO_2.

CDR potential
The technical CDR potential of DACS is primarily limited by three external factors (McQueen et al., 2021; Erans et al., 2022): (1) the unused or excess potential for electrical energy, (2) the unused or excess potential for thermal energy and its temperature level, and (3), the potential for storage of the removed CO_2. Depending on the DAC process, there are different requirements for the electrical and thermal energy needed (e.g., Erans et al., 2022). For example, electrochemical DAC processes depend only on the first and third factors and do not require thermal energy. Wohland et al. (2018) estimated the technical CDR potential of DAC operated with excess renewable electricity in Europe to be 500 $MtCO_2$/year. We are not aware of any study that quantifies a potential for DACS specifically in Switzerland. Periodically, surplus electrical (e.g., Kemmler et al., 2021a) and thermal energy may be available in Switzerland, with realization of previously untapped renewable and thermal potential stalled. However, there are a number of societal goals and applications for which surplus or newly installed energy could be used, for example, to reduce emissions in other applications, for international electricity trading, or for seasonal storage using synthetic fuels. It is an open question whether and what proportion of Swiss energy would be used for DACS. Research on this is currently underway (e.g., SWEET DeCarbCH WP12.4). The development of possible geological reservoirs in Switzerland would probably take decades (see below), and the energy costs would in some cases be significantly higher than abroad, where suitable storage facilities may also be co-located.

1,2,3,4,5,6,7,8 and 14, each excluding reserve land (NFI, 2015; Thees et al., 2017, pp. 42 & 45). Arable land Ct. Fribourg 75,657 ha (Guillaume et al., 2022).

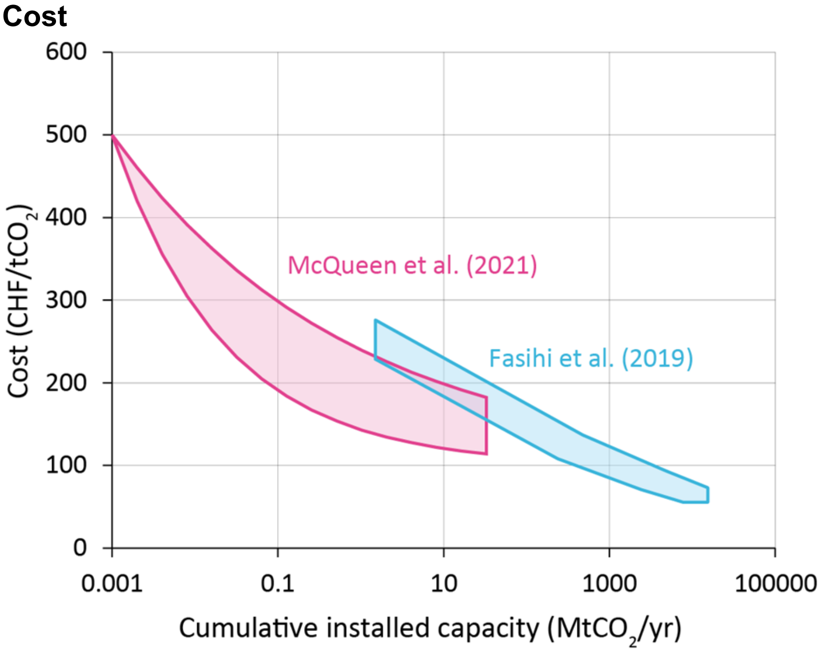

Fig. 5: DAC cost trends estimated by Fasihi et al. (2019) and McQueen et al. (2021) in relation to global cumulative installed DAC capacity.

At CHF 28-926/tCO_2 (USD 30-1000/tCO_2), global cost estimates for DAC vary widely in the scientific literature (e.g., Keith et al., 2018; Krekel et al., 2018; Fasihi et al., 2019; NASEM, 2019; Voskian and Hatton, 2019; McQueen et al., 2021; Kahsar et al., 2022). Influencing variables include the DAC processes used, location, source of electrical and thermal energy, and economies of scale. Generally, costs are expected to reduce with increasing scale (see Fig. 5): e.g., McQueen et al. (2021) estimates a learning rate of 10-20% and Fasihi et al. (2019) 10-15%, which corresponds to a cost range of 120-230 CHF/tCO_2 at a global scale of about 10 $MtCO_2$/year (excl. storage and transport).

Potentials and costs for storing and transporting CO_2

Geological CO_2 storage

Deep, saline aquifers and sedimentary basins, disused oil, gas or CO_2 fields, or CO_2 mineralizing geological formations are suitable for geological storage of captured CO_2. Geological storage in CO_2 mineralizing geological formations results in permanent storage of CO_2, while the other geological storage methods result in near-permanent storage.

Potential
The theoretical potential for geological storage of CO_2 in Switzerland is currently still insufficiently clarified. Chevalier et al. (2010) for the first time roughly estimated the theoretical effective potential in saline aquifers more than 800 m deep at 2,680 $MtCO_2$. Aquifers in the Muschelkalk contributed 708 $MtCO_2$ to the total potential. Based on the availability of new data, the theoretical potential in the Muschelkalk is currently estimated at 52 $MtCO_2$ (Diamond, 2019; Giardini et al., 2021). However, the reduction in the estimated potential in the Muschelkalk does not suggest a change in the potential of the remaining saline aquifers. The current estimates are also still very uncertain, but are to be clarified in more detail in the coming years based on Motion 20.4063.
In Europe, the technical potential for geological storage of CO_2 in aquifers and sedimentary basins is estimated at 232,000-2,120,000 $MtCO_2$ (Consoli and Wildgust, 2017; Kearns et al., 2017). For comparison, the global scale of CDR is estimated at 6,400 $MtCO_2$ /year in 2050 (median of scenario category C1; IPCC, 2022). The potential in CO_2 mineralizing geological formations is likely to be even greater, as a technical potential of 60,000-7,000,000 $MtCO_2$ is estimated for Iceland alone (Snæbjörnsdóttir and Gislason, 2016). Other suitable rock layers with reactive conditions close to Switzerland are suspected in Norway, Turkey, Bosnia and Herzegovina, Croatia, Greece, Italy, Spain, and Germany (Pilorgé et al., 2021, and sources therein).

Cost
Storage costs in saline aquifers are estimated at 6-19 CHF/tCO_2 (7-20 USD/tCO_2; DOE, 2014; NASEM, 2019) and in CO_2 mineralizing geological formations at 2-23 CHF/tCO_2 (2-25 USD/tCO_2) (Gunnarsson et al., 2018; Carbfix, 2021).

Storage of CO_2 in recycled concrete

CO_2 mineralization takes place in the concrete when recycled concrete gets in contact with CO_2. This chemically binds CO_2 in the form of carbonates. CO_2 mineralization is a permanent storage method.

Potential
The technical potential for storing CO_2 in recycled concrete in Switzerland is estimated at 0.56 $MtCO_2$/year in 2050 (Tiefenthaler et al., 2021).

Cost
The authors are not aware of any cost estimates in the scientific literature for storing CO_2 in recycled concrete[4]. A Swiss supplier of this storage method estimates the cost at 200-700 USD/tCO_2; this cost includes capture, liquefaction and transport of CO_2 from biogas upgrading (Stripe, 2021).

CO_2 transport

In most cases, transport of CO_2 from the point of removal, or capture, to the storage site is required. Eckle et al. (2021) investigated how CO_2 could be transported to Norway for geological storage. Different means are proposed depending on how much CO_2 is to be stored each year (Eckle et al., 2021): For quantities up to 100,000 tCO_2/year, it is proposed that the CO_2 be transported by a combination of trucks, a short pipeline, and train to Rotterdam, where it would then be transported by ship to the CO_2 hub of the Northern Lights project. The cost of transport without intermediate storage is estimated at 78 CHF/tCO_2. For medium or large quantities of CO_2 to be transported, transportation via pipeline is proposed. The cost of transport including compression of CO_2 is thereby estimated at 23-29 CHF/tCO_2 (Eckle et al., 2021). Another study by Maggiore et al. (2021) investigated the collection and transport network for CO_2 from 32 point sources in Switzerland. The initial investment is estimated at 2.8-3.2 billion CHF and operating costs are estimated at about 210 million CHF per year, which in combination would correspond to about 36 CHF/tCO_2 for the transport from point sources to the Swiss border (Maggiore et al., 2021). The study by Eckle et al. estimated 8.20 CHF/tCO_2 for this.
Analogous to the transport to Norway, a transport to storage sites in Iceland is possible. This transport chain will be quantified and demonstrated during the pilot project DemoUpCARMA.

[4] Cost estimates exist for carbonation of concrete during or prior to use in the component (e.g., Strunge et al., 2022; Wang et al., 2022), which also involves incorporating slag or silicate aggregates into the concrete that change the CO_2 absorption capacity of the concrete. Because of this, as well as the fact that fresh concrete can absorb more CO_2 than decades-old concrete, the cost estimates are not comparable to the cost estimate for storing CO_2 in recycled concrete.

Discussion and conclusion

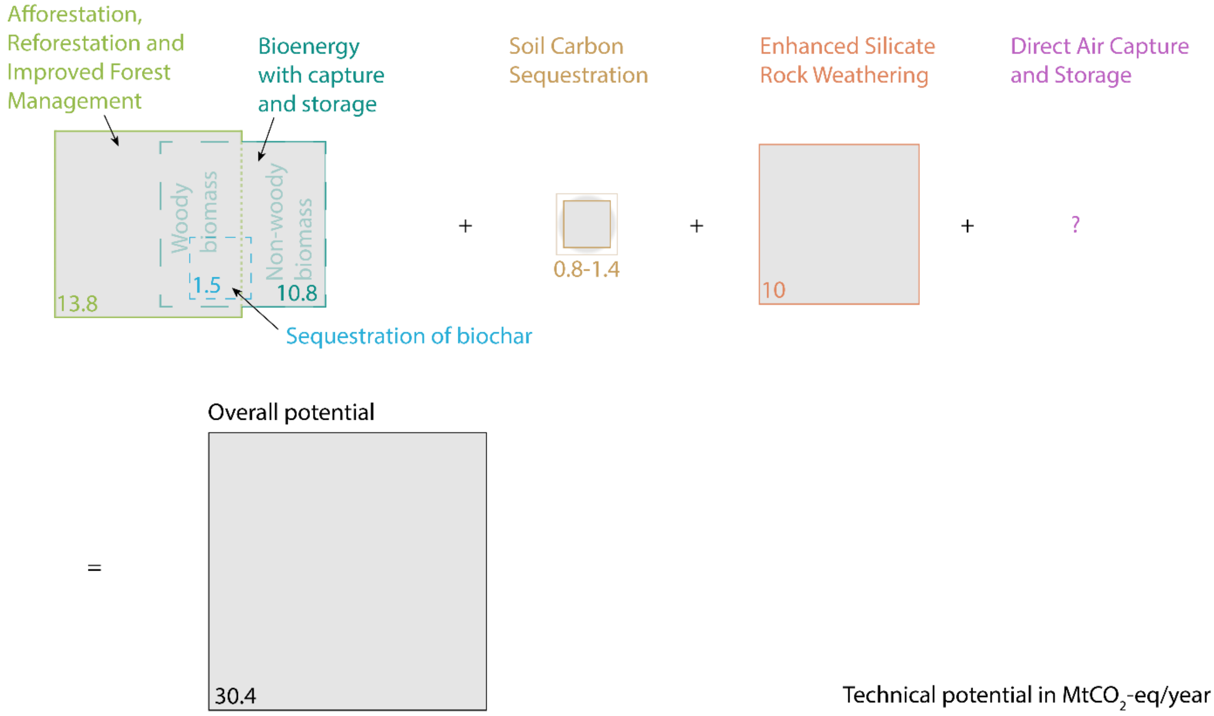

Fig Abb. 6: The estimated technical potentials of the CDR methods considered and the total technical potential in $MtCO_2$-eq/year.

The total technical potential for CDR in Switzerland without DACS is estimated at 30 $MtCO_2$-eq/year (see Fig. 6 and Tab. 1). The same biomass can be used as a storage medium or as a feedstock in afforestation, reforestation and improved forest management, in BECCS and in the production of biochar. However, as the same biomass removed CO_2 only once, the total technical potential turns out to be smaller than the sum of the technical potentials of all CDR methods. While the technical potentials for BECCS and for biochar sequestration are relatively robust, there are still larger uncertainties for afforestation, reforestation, and improved forest management, for SCS, and for ERW. Quantifying the uncertainties is only possible for some components and only represents the results published in various studies. Likewise, the potential for geological storage in Switzerland is still insufficiently clarified. For DACS, no potential estimate specifically for Switzerland was found in scientific publications.

Tab. 1: Estimated technical potentials of the considered CDR methods in Switzerland, comparison with previous studies (Beuttler et al., 2017; Kemmler et al., 2021b) and the amount of CDR used in the "ZERO Basis" scenario of the Energy Perspectives 2050+ (EP2050+) in 2050 (Kemmler et al., 2021b), and estimated costs. The separately considered potentials partly use the same biomass as feedstock, making the combined potential smaller.

* No values published on the composition of the combined potential.

** No values published.

*** Corresponds to the amount of CO_2 mitigated, not the amount of CO_2 removed.

	This study		Beuttler et al., (2018)		EP2050+ Kemmler et al., (2021b)		This study
	Technical potential, separately considered ($MtCO_2$-eq/year)	Technical potential, combined ($MtCO_2$-eq/year)	Theoretical potential separately considered ($MtCO_2$-eq/year)	Theoretical potential, combined (MtCO2-eq/year)	Potential ($MtCO_2$-eq/year)	Used in scenario "ZERO Basis" ($MtCO_2$-eq/year)	Costs (CHF/tCO_2-eq)
Afforestation, Reforestation and Improved Forest Management	13.8	13.8	3.1	*	2	0	0 - 240
Bioenergy with capture and storage (BECCS)	10.8	5.5	5.1	*	**	2.04	156 -190
from woody biomass	5.3	0					
from non-woody biomass	5.5	5.5					
Sequestration of biochar	1.5	0.0	2.2	*	2.5***	0.01	9 - 320
Soil Carbon Sequestration (SCS)	0.8 - 1.4	1.1	3.6	*	**	0	-42 - 93
Enhanced Silicate Rock Weathering (ERW)	10.0	10.0			**	0	80 - 180
Direct Air Capture and Storage (DACS)	?	?				0	28 - 926
Total		30.4		6			-42 - 926

It remains to be seen which part of the technical potential can be realized in the long term. Due to the following aspects, the realizable amount of CDR will be lower compared to the technical potential shown above:

- The realization of the above-mentioned potential partly requires major behavioral changes, for example in land use or how biomass is used materially and energetically within society and industry. If these changes do not occur, the amount of CDR that can be realized will be significantly reduced.
- Biomass for BECCS and biochar can also be used for other purposes without CDR, for example as a substitute for fossil raw materials or energy sources. Captured CO_2 can also be used to produce previously petroleum-based feedstock, such as plastics, synthetic fuels, or pharmaceuticals. This would lead to a corresponding reduction in the achieved amount of CDR.
- It is also open to what extent the Swiss population and economy are willing to bear the costs of CDR. In most cases, a reduction of greenhouse gas emissions will be the cheaper and technically simpler measure than balancing greenhouse gas emissions with CDR.
- The quantified potentials do not yet include any greenhouse gas emissions that result from the application of the respective CDR method. This will reduce the net amount

of CDR achieved. Only a life cycle emissions analysis can estimate how large the reduction is likely to be.

- CDR, as noted, includes "human activities that remove CO_2 from the atmosphere and store it permanently in geological, terrestrial, or oceanic reservoirs or in products" (IPCC, 2022). In this context, it has not yet been scientifically defined what storage period "permanently" corresponds to. Once this is defined, the potential of CDR methods with shorter storage durations will no longer apply. These can still help to temporarily remove CO_2 from the atmosphere, but would then have to be repeated to store the non-permanent part.

Initial rough estimates indicate that the ecological CDR potential is likely to be about half as large as the technical potential and would therefore also be larger than previously assumed. From an economic point of view, CDR not only leads to costs in Switzerland, but also opens up the possibility of participating in new, lucrative global economic sectors as well as reducing costs due to the effects of climate change. Techno-economic simulations can help to evaluate the economic CDR potentials as well, although uncertainties for some CDR methods are likely to remain large due to the still small scale. The CO_2 removal effectively realized by 2030 or 2050 will critically depend on the political-economic framework of an effective cross-sectoral national as well as international climate policy, and the abatement costs of greenhouse gases (alternative propulsion, heat pumps, synthetic fuels, etc.). An active, open dialogue with the public can also help to ensure that the purpose and operation of CDR methods used in Switzerland are understood and widely supported.

In an earlier assessment of the potential for CDR in Switzerland by Beuttler et al. (2019), the total theoretical potential was estimated to be around 6 $MtCO_2$-eq/year (see Table 1). On the one hand, the differences to the estimate of the present study stem from the fact that ERW and timber harvesting were not considered by Beuttler et al. On the other hand, in Beuttler et al. only the previously unused biomass for energy use from Thees et al. (2017) was provided as feedstock for BECCS (dry weight approx. 101,000 t/year), whereas in the present study also the already used biomass was included (dry weight approx. 246,000 t/year). For example, biomass that is currently already burned in waste recycling plants or cement plants. The Swiss Federal Council as well as the Swiss cement industry association envisages retrofitting these plants with CCS (Cemsuisse, 2021; Federal Council, 2022), which would allow a CDR potential of the already used biomass to be realized.
In the context of the Energy Perspectives 2050+ (Kemmler et al., 2021a; 2021b; see Tab. 1), the potential of forest management in Switzerland was estimated to be several hundred thousand tons to a maximum of 2 $MtCO_2$-eq/year, although it was not defined what class of potential the estimate was. It was further estimated that over 40 $ktCO_2$ could be mitigated with the production of biochar from one PJ of biomass. With an annual biomass potential of 63 PJ, this would be equivalent to 2.5 $MtCO_2$/year. However, this value quantifies how much CO_2 could be avoided and not how much CO_2 could be removed from the atmosphere. Furthermore, cement is also discussed as a CO_2 sink and the CDR potential is estimated at 1.1 to 2.5 $MtCO_2$/year. For ERW, only a global potential is quantified. No potentials are mentioned for BECCS and DACS. CDR is also used in the scenarios of the Energy Perspectives 2050+. In the scenario "ZERO Basic", for example, 2.04 $MtCO_2$/year of CDR were used from BECCS and 0.01 $MtCO_2$/year from biochar in 2050 (see Tab. 17, Kemmler et al., 2021b). For Switzerland to reach net zero GHG emissions in 2050 in this scenario, an additional 4.7 $MtCO_2$/year are removed by DACS installed and operated abroad.

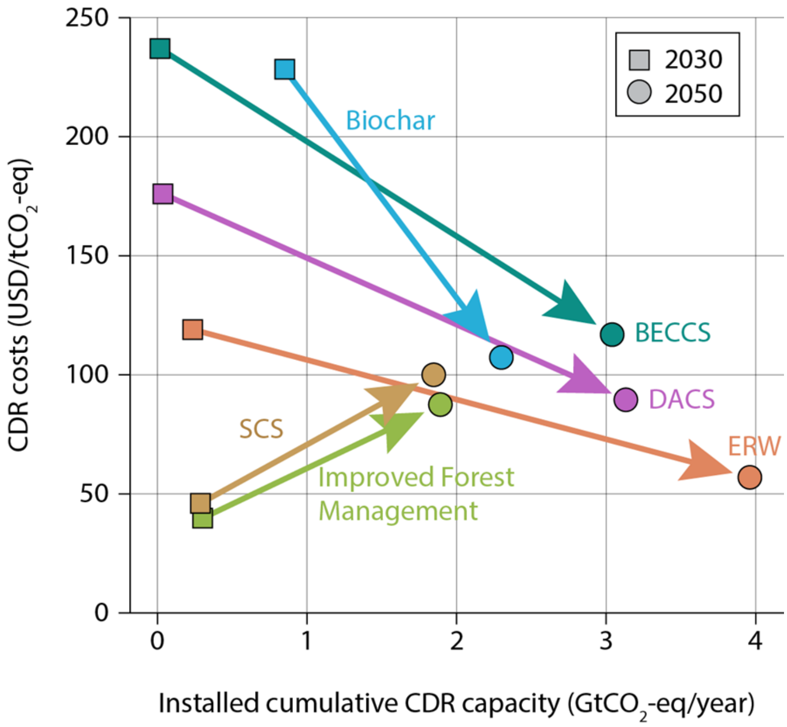

Fig. 7: Estimated global cost trends for the considered CDR methods between 2030 and 2050 as a result of scaling. Figure adapted from Kahsar et al. (2022).

The estimated costs for the different CDR methods vary widely within the literature reviewed, ranging from -42 to 926 CHF/tCO_2-eq. Rather low-cost CDR methods, at least initially, are improved forest management and SCS. All other methods are likely to become less expensive as they scale up. Kahsar et al. (2022) concludes that the variation among the CDR methods considered will become smaller in the future (see Fig. 7). In general, cost estimates for the future are uncertain.

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Glossary

Carbon Capture and Storage (CCS; IPCC, 2021): “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.” CCS is a process to reduce emissions and does not result in the removal of CO_2 from the atmosphere. In BECCS, CCS is used to prevent CO_2 that has already been removed from the atmosphere from re-entering the atmosphere despite the use of biomass for energy, and at the same time to store it permanently.

Mitigation of climate change (UNFCCC, 2022): “In the context of climate change, a human intervention to reduce the sources or enhance the sinks of greenhouse gases. Examples include using fossil fuels more efficiently for industrial processes or electricity generation, switching to solar energy or wind power, improving the insulation of buildings, and expanding forests and other "sinks" to remove greater amounts of carbon dioxide from the atmosphere.”

Carbon Dioxide Removal (CDR; IPCC, 2021): “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 (DACS), but excludes natural CO_2 uptake not directly caused by human activities.” For example, an excluded indirect effect would be the uptake of CO_2 by water bodies due to Henry's Law. CDR can be used synonymously with negative CO_2 emissions.

CO_2 sink: see sink.

Negative Emission Technologies (NET): Negative emission technologies are used to remove CO_2 and other greenhouse gases from the atmosphere. See CO_2 removal or greenhouse gas removal (not discussed in this report).

Net negative greenhouse gas emissions: State in which more metric-weighted greenhouse gases are removed from a reference system by anthropogenic greenhouse gas sinks than are emitted into the reference system by metric-weighted anthropogenic greenhouse gas emissions.

Net zero greenhouse gas emissions, greenhouse gas neutrality (IPCC, 2021): “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.
Note 1: GHG neutrality and net zero GHG emissions are overlapping concepts. The concept of net zero GHG emissions can be applied at global or sub-global scales (e.g., regional, national and subnational). At a global scale, the terms GHG neutrality and net zero GHG emissions are equivalent. At sub-global scales, net zero GHG emissions is generally applied to emissions and removals under direct control or territorial responsibility of the reporting entity, while GHG neutrality generally includes anthropogenic emissions and anthropogenic

removals within and beyond the direct control or territorial responsibility of the reporting entity. Accounting rules specified by GHG programmes or schemes can have a significant influence on the quantification of relevant emissions and removals.
Note 2: Under the Paris Rulebook (Decision 18/CMA.1, annex, paragraph 37), parties have agreed to use GWP_{100} values from the IPCC AR5 or GWP_{100} values from a subsequent IPCC Assessment Report to report aggregate emissions and removals of GHGs. In addition, parties may use other metrics to report supplemental information on aggregate emissions and removals of GHGs."

Sink (IPCC, 2021): "Any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere (UNFCCC Article 1.8 (UNFCCC, 1992))." A sink that permanently removes CO_2 through anthropogenic activities is termed Carbon Dioxide Removal (CDR).

Sequestration: Process of storing greenhouse gases in geological, terrestrial, or oceanic reservoirs or in products.

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Appendix

A1 Details of the estimation of the CDR potentials of BECCS.

Table A1 shows the converted amount of CO_2 contained in the sustainably available biomass for energy use in Switzerland, leading to CDR in the case of energy use with CCS as BECCS. Thees et al. (2017) estimated the sustainably achievable biomass potentials for energy use in Switzerland. Here, part of the biomass is directly used for energy (woody biomass), while another part is partially converted to biogas and both the biogas and the remaining biomass are used for energy (non-woody biomass such as agricultural byproducts, farmyard manure, organic industrial waste, organic sweepings, green waste, and sewage sludge). The carbon content of dry biomass is estimated to be 3.8 MtC/year using literature values (based on Lamlom and Savidge, 2003; Oreggioni et al., 2017; Phillis2, 2021; Bowman et al., in prep.). Assuming that each carbon molecule removed by the plant is equivalent to one molecule of CO_2 previously removed from the atmosphere, the biomass contains 12.0 MtCO_2-eq/year. This amount would be re-emitted into the atmosphere during energy use without CCS. If 90% of the CO_2 is captured and permanently stored during energy use by CCS, this results in a technical CDR potential of 10.8 MtCO_2/year for BECCS.

Tab. A1: The biomass sustainably available for energy use in Switzerland, the estimated carbon content, and the converted stored amount of CO_2 that the biomass previously removed from the atmosphere.

	Feedstock	Sub-categories	Dry weight (t tw)	Primary energy content (PJ)	Potential biomethane production (PJ)	C content (t_C/t dw)	Source	C in biomass (Mt/yr)	C in biogas (Mt/yr)	CO_2 stored in biomass (Mt/yr)
			Source: Thees et al., 2017							
Woody	**Forest wood*1**		**1822650**	**26.1**				**0.894**	**0.000**	**3.276**
		Hardwood (with bark)	1183770	16.1		0.48	Lamlom and Savidge	0.568	0.000	2.082
		Softwood (with bark)	638880	10.0		0.51	Lamlom and Savidge	0.326	0.000	1.194
	Wood from landscape maintenance*1		**305257**	**4.8**				**0.156**	**0.000**	**0.570**
		Residential area	61863	1.0		0.51	Bowman et al., in prep.	0.032	0.000	0.116
		Road sides	73834	1.1		0.51	Bowman et al., in prep.	0.038	0.000	0.138
		Agricultural area	56855	0.9		0.51	Bowman et al., in prep.	0.029	0.000	0.106
		Groves and schrubberies	22800	0.4		0.51	Bowman et al., in prep.	0.012	0.000	0.043
		Hedges	48633	0.8		0.51	Bowman et al., in prep.	0.025	0.000	0.091
		Shore area	41272	0.6		0.51	Bowman et al., in prep.	0.021	0.000	0.077
	Waste wood		**653676**	**11.7**				**0.333**	**0.000**	**1.222**
		Natural wood (only mechanically processed)	152415	2.7		0.51	Bowman et al., in prep.	0.078	0.000	0.285
		Glued, painted, laminated, varnished wood	338199	6.0		0.51	Bowman et al., in prep.	0.172	0.000	0.632
		Halogen-organic compounds (e.g. plated with PVC)	100303	1.8		0.51	Bowman et al., in prep.	0.051	0.000	0.187
		Treated with wood preservatives (Railway sleepers, electric poles, etc.)	62760	1.1		0.51	Bowman et al., in prep.	0.032	0.000	0.117
	Wood residues		**458041**	**7.6**		**0.51**	**Bowman et al., in prep.**	**0.234**	**0.000**	**0.856**
Non-woody	**Agricultural crop by-products**		**134485**	**2.6**	**1.0**			**0.066**	**0.025**	**0.241**
		Cereals (chaff only)	84894	1.7	0.6	0.49	Phyllis2	0.042	0.014	0.152
		Other crops	28559	0.6	0.3	0.49	Phyllis2	0.014	0.007	0.051
		Intermediate crops	21032	0.4	0.1	0.49	Phyllis2	0.010	0.003	0.038
	Animal manure*1		**1692924**	**26.9**	**9.9**			**0.975**	**0.246**	**3.571**
		Cows	1279489	20.2	7.0	0.59	Oreggioni et al., 2017	0.750	0.175	2.748
		Pigs	81134	1.1	0.5	0.54	Phyllis2	0.044	0.012	0.161
		Horses	178212	3.2	1.4	0.54	Phyllis3	0.097	0.035	0.355
		Sheep	104916	1.6	0.7	0.54	Phyllis4	0.057	0.017	0.209
		Goat	20964	0.3	0.1	0.54	Phyllis5	0.011	0.003	0.042
		Poultry	28209	0.4	0.2	0.54	Phyllis6	0.015	0.005	0.056
	Organic fraction of household garbage		**210455**	**3.9**	**0.4**			**0.103**	**0.010**	**0.378**
		Biogenic fraction	35336	0.5	0.4	0.52	Phyllis2	0.018	0.010	0.067
		Paper, cardboard, etc…	157734	3.0	0.0	0.48	Phyllis2	0.076	0.000	0.277
		Other organic fraction	17385	0.4	0.0	0.53	Bowman et al., in prep.	0.009	0.000	0.034
	Green waste from households and landscape		**391238**	**5.8**	**4.5**			**0.206**	**0.111**	**0.756**
		Already collected separatly today	264028	3.9	3.0	0.53	Bowman et al., in prep.	0.140	0.075	0.513
		Organic fraction of the household garbage*2	127211	1.9	1.5	0.52	Phyllis2	0.066	0.036	0.243
	Commercial and industrial organic waste		**238186**	**2.7**	**2.2**			**0.124**	**0.054**	**0.453**
		Food processing	172039	1.9	1.5	0.52	Phyllis2	0.089	0.037	0.328
		Catering	32559	0.6	0.5	0.52	Phyllis2	0.017	0.013	0.062
		Retailers	25732	0.2	0.2	0.52	Phyllis2	0.013	0.004	0.049
		Tobacco industry	1221	0.0	0.0	0.50	Assumption: 50% C	0.001	0.000	0.002
		Paper production	5486	0.0	0.0	0.48	Phyllis2	0.003	0.000	0.010
		Printing industry	0	0.0	0.0			0.000	0.000	0.000
		Textile production	945	0.0	0.0	0.50	Assumption: 50% C	0.000	0.000	0.002
		Pharmaceutical industry	204	0.0	0.0	0.50	Assumption: 50% C	0.000	0.000	0.000
	Sewage sludge from central t	**Fresh sludge (before Fermentation)**	**347272**	**4.9**	**2.6**	**0.51**	**Phyllis2**	**0.177**	**0.065**	**0.649**
	Sum			**97.0**	**20.5**			**3.267**	**0.511**	**11.973**

Methane in Biogas: assuming a mole fraction of 40% CO_2 except for manure

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