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Carbon removal, net zero, and implications for Switzerland

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In order to find solutions to society's biggest challenges, E4S encourages discussions and diversity of opinions on topics of crucial importance. The views and opinions expressed in documents published by E4S are those of their authors and do not necessarily reflect the official policy or position of E4S.

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1. EXECUTIVE SUMMARY

This E4S white paper provides an overview of carbon removal in the context of climate action towards net zero, covering the main points policymakers and organizational leaders should keep in mind.

We will make the case for carbon removal, which in this paper includes carbon capture, utilization and storage (CCUS) and negative emission technologies (NET), as an important but small part of climate action in the 2-3 critical decades we have to stabilize our climate and stop biodiversity loss.

This insight is key for properly designing and governing carbon removal, as a complement to deep emission reductions based on sufficiency, efficiency, and clean energy. We will argue that CCUS and NET are important contributions to broader climate action, with potential limited to several percent of current emissions. This is not a contradiction: no single approach will solve the climate crisis.

After decades of climate inaction and ever-increasing emissions, despite increasingly urgent and precise warnings by the IPCC, several successful international agreements (Kyoto, Paris), unprecedented mobilization of the civil society around the world, and more frequent extreme weather events (flooding, drought, fires, temperature extremes) - the time to act is running out, if we want to keep warming within 1.5°C above pre-industrial times. We have less than a decade to globally halve emissions[1], and less than 30 years to reach -90%. We may need costly, difficult to implement measures like carbon removal, which we could have easily avoided with timely reductions.

To stay within 1.5°C warming, IPCC's AR6[2], published in August 2021, defines the remaining carbon budget we can safely emit at 300-400 Gt CO_2. The 300 Gt limit will be reached around 2027-2028, unless we massively reduce our emissions almost immediately. This extremely short window limits the role of technologies still in R&D, and the time to deploy existing ones - suggesting an emphasis on policy, behavior, and economic measures.

In this context, carbon removal, both CCUS (carbon capture before it reaches the atmosphere) and NET (negative emissions, removing carbon from the air and storing it at climate-relevant time scales) will have an important role to play. Today, carbon removal beyond the fast natural carbon cycle (i.e. photosynthesis and storage in living biomass and soils) is experimental and small-scale. Worldwide, it is highly unlikely to scale beyond 5-10% of current emissions (i.e. 3-6 Gt CO_2e)[3], at least in the 2-3 critical decades to come, during which we must stabilize the climate (IPCC AR6 WG3 will include a new estimate). Yet it can still provide significant climate benefits such as reaching net zero if combined with deep decarbonization.

Climate warming affects humans directly and indirectly, by degrading ecosystem services on which we depend for survival, such as food, medicine, pollination, or nutrient cycling[4]. Protecting ecosystem services is one of the main reasons for climate action. Many biological carbon removal measures, if properly implemented, can offer significant biodiversity co-benefits, even at relatively small scales.

What carbon removal cannot provide is a stable climate with business as usual, without deep cuts in emissions.

Since 1972, CCS has been used commercially, mostly to enhance oil recovery from depleted oil fields (details in the section "CCS+EOR"); today it removes 0.1% of current emissions. The so far committed expansion plans will not significantly change this ratio. Given the investment and deployment cycle, carbon removal is unlikely to play more than a marginal role before the 2030s.

It is essential to keep in mind the purpose of carbon removal: help reach net zero by removing the residual emissions, after sufficiently deep decarbonization. Additionally, it should provide real biodiversity co-benefits, and avoid any negative ecosystem impacts. This is not how CCUS has developed historically (to extract more oil from depleted fields) or is viewed by big players today: to extend the fossil era, prolong the lifetime of stranded assets like coal power plants, open new markets for oil companies (solvents), or simply benefit from available "green" subsidies. Stabilizing the climate is missing from the goals of almost all main players.

Unless this purpose (and the actions it leads to) changes, carbon removal will not meaningfully contribute to climate action, even distracting from real action, while transferring wealth from taxpayers to corporations.

Carbon removal is costly and requires funding to be deployed at a meaningful scale. Funding can be based on a carbon tax plus removal subsidy of several hundred dollars per ton CO_2 or through some form of a carbon removal mandate, directly or via a cleanup fund. One such proposal for Switzerland, the Swiss Climate Cleanup Fund, is developed in the E4S working paper "Climate Cleanup Fund - getting to Swiss Net Zero".

In practice, carbon removal will only work within a framework of international cooperation, except perhaps for small-scale projects with significant local ecosystem benefits. If positioned as a complementary measure to reach net zero based on deep decarbonization across all sectors, the moral hazard can be limited - carbon removal will not be seen as a possible substitute for significant emission cuts. With such international cooperation and proper positioning, carbon removal can play a limited but very important role in our task of stabilizing the climate.

For Switzerland, given its density, fragile ecosystems, faster warming already reaching 2°C, limited available biomass, and relatively high emissions from cement and waste incineration, we stress the importance of nature-based climate action with biodiversity co-benefits, especially wetland restoration, biochar and soil carbon projects. Additionally, CCS with local geological storage should be developed for cement plants and incinerators, as well as limited BECCS. The realistic potential in Switzerland is around 5 Mt per year, corresponding to the last 10% of territorial emissions, reaching net zero together with deep decarbonization. Carefully designed and monitored, carbon removal measures could also strengthen the resilience of fragile ecosystems.

The importance of carbon removal goes well beyond the last 5-10% of current emissions, by implicitly defining goals for sufficiency, efficiency, and renewable energy, and setting an "objective" carbon price. The realistically achievable carbon removal potential determines how deep and how fast we must reduce emissions to stay within the remaining 1.5°C budget. Carbon removal also sets an objective, "technical" as opposed to "political" price for emitting CO_2, creating a strong signal to accelerate climate action. Nature-based carbon removal also offers rapid and significant biodiversity benefits, if designed and monitored for this goal. Metaphorically, the "tail" of carbon removal could be wagging into action the "dog" of deep decarbonization.

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2. OVERVIEW OF CLIMATE ACTION

State of the Climate in 2021, based on IPCC AR6 and SR15

Since 1896, when Svante Arrhenius[5] quantified the climate sensitivity of the already well-known greenhouse effect of atmospheric CO_2, we have been able to estimate with remarkable precision to what extent human activities cause climate warming. IPCC's six assessment reports since 1990 have summarized one of the most critically studied areas of human knowledge. To date, 26 annual UN climate conferences (COPs) have pressured the biggest emitters to act, with increasing urgency. Major agreements have been reached, such as Kyoto 1997 and Paris 2015.

Yet emissions continue to rise and are now about 50% higher than in the Kyoto year, 1997. After several decades of inaction, time is running out, and difficult-to-implement measures such as removing CO_2 from the atmosphere may be required, which we could have easily avoided with timely reductions.

Relative to the pre-industrial baseline (average temperature 1850-1900), the world is already 1.2°C warmer on average, with significant regional variations: for example in Switzerland the average temperature is around 2°C higher[6]. The effects of global warming are highly non-linear[1], and 2.0°C warming is much worse than 1.5°C, making the Earth much less habitable for humans and ecosystems on which we depend for survival. 2.5°C warming would be much worse still. Yet, despite recent progress (COP21-COP26, 2015-2021), current policies[7] still lead us towards 2.7°C, as of November 2021.

Remaining carbon budget, getting to Net Zero

To limit global warming to 1.5°C, the 2021 IPCC AR6[2] estimates the remaining carbon budget at 300 Gt CO_2 (relatively safe) to 500 Gt CO_2 (highly uncertain). Without massive emissions reduction, the safe limit will be reached in 2027-2028. Any additional CO_2 emitted will have potentially dangerous consequences unless rapidly removed from the atmosphere. If we waste another decade, 1.5°C will be out of reach[1,2].

Net zero, for a country or organization, signifies that no carbon is added to the atmosphere on a net balance. In practice it means first that emissions are significantly reduced, and that any residual carbon emitted in the atmosphere will be removed. It does not include any compensation. To be useful and lead towards a 1.5°C world, it also means that cumulative emissions should be compatible with the remaining carbon budget, so it includes a pathway to net zero, according to IPCC on average -50% by 2030 and at least -90% by 2050 relative to 2020, with faster reductions for big emitters.

Is CO_2 compensation part of climate action?

Compensating CO_2, i.e. paying someone else to reduce their emissions somewhere in the world and applying the reduction to your own emissions, is often seen as an easy and cost-efficient way to get to net zero. Unfortunately, this appears highly problematic for several reasons: (a) it is hard to ensure the reductions are real, additional, and permanent, (b) projects are often double-counted, (c) the projects may be crowding out the host country's own much needed net-zero efforts, and (d) the framework for such cooperation under the Paris Agreement (Art.6) just adopted at COP26, is still unclear.

Specifically, to avoid double counting, Art.6.4 requires host countries to apply “corresponding adjustments”, i.e. exclude the transferred credits from their own commitments (NDCs). It is too early to evaluate how well this will work in practice. There is no shortcut for effective climate action.

Overview of climate action by type and effect

Climate action can be classified in seven distinct types (adapted from Minx et al 2018[8]) ranging from avoiding emitting activities to adapting to live with a warmer climate:

1. Sufficiency: avoid or reduce activities emitting CO_2. This includes for example not flying, reducing consumption, using less floor space per person.
2. Efficiency: for a given activity, use less energy and emit less CO_2. Deploy more efficient processes or technology such as LED lights or train travel; build with wood instead of concrete (Note: this is effective only if the rebound effect can be limited, see below for details).
3. Clean energy: replace fossil energy by renewable sources, minimize embodied CO_2.
4. Carbon capture: capture the CO_2 before it reaches the atmosphere. Captured CO_2 can be stored underground (Carbon Capture and Storage, CCS) or transformed for example to chemicals or plastics (Carbon Capture and Utilization, CCU). In some cases both U and S can be achieved together, such as in the utilization of carbon in building materials (Carbon Capture, Utilization and Storage, CCUS).
5. Negative emissions (NET, also referred to carbon dioxide removal or CDR): remove CO_2 from the atmosphere, using biological or chemical processes, such as planting trees, restoring ecosystems, or using chemical sorbents, and store it at climate-relevant time scales (see NET section for details).
6. Solar radiation management (SRM): methods to deliberately reduce anthropic global warming by increasing Earth’s average albedo (reflectivity). This could for example be achieved by mimicking volcano eruptions and injecting millions of tons of sulphur aerosols in the stratosphere.

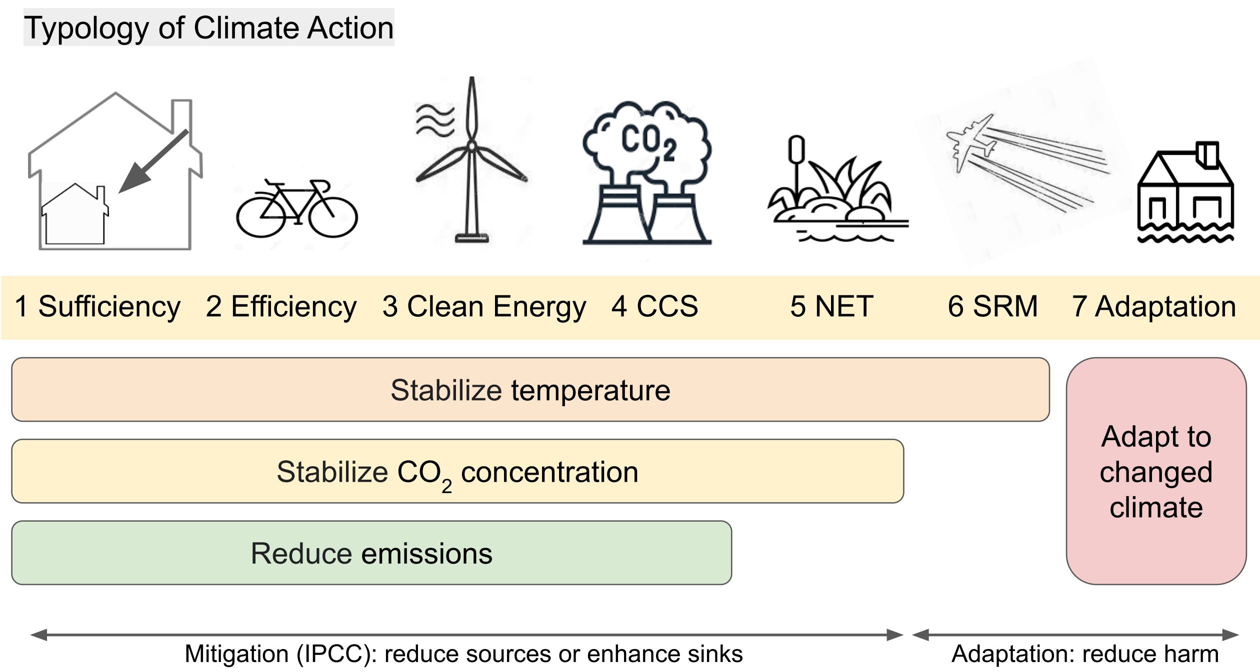

Fig. 1: Types of climate action (see text for acronyms and explanation)

7. Adapt to climate change: this can range from building floodwalls, planting heat-resistant crops, painting roofs in white, to abandoning cities or even countries as they become uninhabitable.

Actions 1-4 reduce emissions; action 5 reduces CO_2 atmospheric concentration (which, among other effects, reduces temperature), action 6 reduces temperature only, without having much impact on other consequences of increased CO_2 concentration, such as ocean acidification, and action 7 adapts to the changed climate.

All approaches have limitations, and some can be dangerous

There are no technical barriers to sufficiency, only cultural ones and the need to adjust societal norms, structures and incentives. The benefits of efficiency are mainly limited by the rebound effect, where efficiency improvements reduce the cost of production or use, leading to higher demand, in turn reducing energy saving, and sometimes increasing aggregate energy use. Clean energy is limited by the speed of deployment - it would take decades to replace the 500 EJ fossil energy used today. Fortunately, with sufficiency and efficiency, this much energy will not be needed[9,10].

CCS is limited by the high energy and financial cost (see section "Cost overview"), and its existing infrastructure. It removes 80-95% of CO_2, less on a lifecycle basis (including resources to make the CCS equipment), and none of the other pollutants, such as $PM_{2.5}$, sulphur dioxide, benzene, ozone, nitrogen oxides, carbon monoxide[11]. Due to efficiency loss (more fuel used), such non-CO_2 pollutants may actually increase.

CCU is limited by the use of CO_2 as such, with most uses requiring the breaking of the strong C-O bonds at a great energy cost. Additionally, carbon used in CCU quickly returns to the atmosphere, for most applications.

Biological negative emissions need a lot of land and water, and must be carefully designed for biodiversity co-benefits, ensuring no ecosystem damage, further limiting their potential. Ensuring permanence is challenging. Chemical NETs are extremely expensive, financially and in terms of energy, and are highly unlikely to scale quickly (see analysis in section "Technical analysis of limits to NET").

SRM has never been tested (although aerosols from volcanic eruptions do cool the climate), and poses many ethical and governance issues, as well as numerous side effects. The climate effects will be highly uneven, with winners and losers, whose whole countries could become uninhabitable. Who gets to decide about deployment? Could this potentially lead to conflict and war?

This paper covers CCUS and NETs (#4-5), as a complement to deep reductions based on #1-2-3. We will argue that CCUS and NETs are important components of broader climate action, with potential limited to several percent of current emissions.

3. CARBON CAPTURE, UTILISATION AND STORAGE (CCUS)

Carbon capture: sources, technologies, current deployment

Carbon capture (CC) is a process to capture CO_2 before it enters the atmosphere, storing it safely for hundreds or thousands of years, typically in geological formations, such as saline aquifers, depleted oil fields, or basalt formations (CCS) or using the CO_2 (CCU). CC always includes CO_2 separation, compression, transport, and storage or utilisation.

It can be applied to large point sources such as cement, steel or chemical plants, coal or gas power plants, or waste incinerators, typically emitting >100 kt CO_2 per year.

CCS has been used since 1972. As of mid-2021, 26 commercial facilities (>100 kt CO_2/yr) are in operation[12], of which 12 in the US, 4 in Canada, 3 in China, for a total of 40.12 Mt CO_2/yr, or approximately 0.1% of world's total emissions. There are no CCU facilities at this scale.

Per sector, 24 of the 26 facilities are in the petro-chemical industry (gas, oil, ethanol, methanol, hydrogen, fertiliser, bulk chemicals), plus one coal power plant and one steel plant. There are small-scale pilot plants in cement and waste incineration, but no commercial facilities yet.

There are three main processes to separate CO_2 from the flue gas (concentration 3-15%, typically 10%):

1. Post-combustion, by far the most common, used in 25 of 26 commercial plants, as it can be retrofitted to existing facilities. Technically, it is based on a liquid solvent which absorbs CO_2 from the flue gas, which is then heated to release high-purity CO_2. Membranes are a promising alternative to solvent-based separation, used in a number of pilot projects; no commercial facility (>100 kt CO_2/yr) is yet deployed.
2. Pre-combustion, which chemically separates the fuel (oil, gas, coal) into CO_2 and H_2 before using the hydrogen as fuel. This is a complex process that cannot be retrofitted to existing power plants, and is not yet deployed in commercial facilities.
3. Oxyfuel combustion uses unchanged fuel, which is burned in pure oxygen, producing pure CO_2 mixed with water vapor. Vapor is easy to remove by cooling the flue gas, and the whole process is very simple. Oxyfuel is used today in several coal power plants without CCS, but only in one commercial CCS facility. The main barrier is the cost of pure oxygen.

Separating CO_2 from the flue gas is energetically expensive, increasing the fuel consumption of a power plant[13] by 11%-40%, typically 20-25%. In CCS, 2/3 of the energy is used for separation, 1/3 for compression and transport[14].

CCS: transport and storage of CO_2

Once separated, CO_2 can easily be transported[15] by pipeline, ship, or for small quantities and distances, by rail or truck. Existing oil and gas pipelines can be adapted. Currently there are very few CO_2 operational pipelines, mostly in the US, linked to EOR. 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.

"CCS Hubs" built around storage facilities like "Northern Lights", linking several capture facilities by pipelines, could generate economies of scale, facilitate learning, and lower costs.

The main transport-related challenges are the cost of building or retrofitting pipelines, the energy requirements to compress and transport CO_2 at scale, and public acceptance. Landlocked countries like Switzerland are dependent on transport via other countries to reach the sea. One option for Switzerland would be repurposing the old Genoa to Collombey oil pipeline (E50), unused since 2015. This is far from easy: there is little experience in retrofitting pipelines. 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.

Permanent geological storage is abundant almost all around the globe, in saline aquifers, depleted oil fields, or basalt formations. On land, saline aquifers and depleted oil fields are more common, much of the sea bed and oceanic islands are made of basalt, offering massive potential storage, many orders of magnitude beyond what is needed[16]. In Switzerland, there is a wide range of estimates[17,18], from 50 Mt to 2680 Mt CO_2, the uncertainty reflecting the lack of experimental validation. Most estimates suggest Swiss capacity to store at least decades of captured emissions.

CCS+EOR (Enhanced Oil Recovery)

After separation, CO_2 must be permanently stored in suitable geological formations. Since the first operational commercial facility opened in 1972, the main purpose of CCS has been Enhanced Oil Recovery (EOR), corresponding to 90% of historical capacity. Even today, 75% of today's storage capacity is in EOR, with the remaining 25% in permanent geological storage.

EOR is a process where the CO_2 is injected in a depleted oil field, where oil extraction otherwise ceases to be profitable. Injected high pressure CO_2 will dissolve in oil, liquefying it and allowing extraction of most of the remaining oil. From a climate perspective, this is problematic, as the extracted oil will be burned, emitting more CO_2 than was used to extract it, *increasing* total emissions instead of reducing them. The exact ratio is complex to calculate[12] and depends on two parameters, the crude oil recovery ratio, typically 2-3 barrels of oil per ton CO_2, and the additionality of the extracted oil (short-term displacement effect vs. long-term oil market increase). Longer-term, the emissions of burning EOR oil correspond to 1.5-2 times the CO_2 stored, with significant variation[12], *increasing* net emissions.

CCU: tiny today, unlikely to grow much anytime soon

In common with CCS, carbon capture and utilisation (CCU) is a process to capture CO_2 before it enters the atmosphere. Then, instead of storing the CO_2 underground, it is used in industrial products, before it re-enters the atmosphere. Therefore, CCU does not directly contribute to removing CO_2. Its contribution depends on how CO_2 was produced before: (1) as a by-product of ammonia production, in which case CCU will have no effect, or (2) by burning natural gas, in which case CCU replaces fossil with atmospheric carbon, avoiding more fossil-based CO_2 entering the atmosphere. It may be viewed as "carbon recycling".

Over 90% of today's total use of CO_2, around 250 Mt p.a., is used in fossil fuel-based urea production and EOR[19]. Food and beverage use represents 6%, with the rest in metals, chemicals, water treatment, and health care.

Today's CCU market based on captured CO_2 is tiny, less than 0.1% of Swiss territorial emissions, mainly used in greenhouses to accelerate plant growth, and for carbonated drinks, if food-purity CO_2 can be obtained. In all cases, the CO_2 is released within days.

Beyond capture limitations, the uses for CO_2 as such are very limited, with most uses requiring the breaking of the strong C-O bonds at a great energy cost. This is the fundamental limit to any future development.

Potential future large-scale use includes chemical feedstock for plastics production, intermediate high-value materials like methanol, synthetic liquid fuels, or synthetic methane. All replace fossil fuel feedstock by captured atmospheric CO_2, which re-enters the atmosphere within days or weeks, when the fuel is burned, or plastic incinerated at the end of its life. The benefit is obviously to eliminate the use of additional fossil fuels, making the whole cycle potentially almost carbon-neutral, if 100% clean energy is used. None of this exists today at scale.

This process is very energy-intensive, requiring 2-3 times more energy to produce the synthetic fuel, compared to the chemical energy contained in the produced fuel, typically 100 MJ to produce a kg of liquid fuel containing 45 MJ of energy when burned. This means that the required scale of the energy system to achieve any meaningful substitution of today's plastic or fuel consumption will be very likely unreachable for decades: it would not only require replacing today's annual 500 EJ of fossil energy by renewables, but much of it multiplied by 2-3 (see section "Technical analysis of limits to NET").

Limitations of CCUS

In summary, carbon capture is limited by its high energy and financial cost. Additionally, if the stored CO_2 is used for EOR, it ends up *increasing* emissions and contributing to the climate crisis. CCS removes 80-95% of CO_2, and none of the other pollutants, which for coal power plants include $PM_{2.5}$, sulphur dioxide, benzene, ozone, nitrogen oxides, carbon monoxide (burning gas is cleaner, not producing SOx or benzene, and little NOx and CO). The other pollutants actually increase, due to the additional fossil fuel used to power CCS itself. On a lifecycle basis, including the energy and CO_2 cost of building the needed equipment, only 63–82% of CO_2 is removed, with the high end of this range requiring expensive oxyfuel capture[13].

CCU is limited by the small market of using CO_2 without further transformation. CO_2 is a very stable molecule, requiring a lot of energy to transform into feedstock or fuel, generally 2-3 times the energy contained in the fuel. Long term, a less energy-constrained future may be imaginable, reducing the importance of this constraint, but almost certainly not for many decades.

There are no insurmountable issues in transport or storage, but many engineering challenges such as cost, energy requirements, risks, public perception and acceptance, and the time to build the infrastructure.

Finally, the potential of CCUS will decrease with the move away from fossil energy, only partially compensated by bioenergy with carbon capture and storage (BECCS), described in the chapter on NETs. Once we completely eliminate fossil fuels, as we must do for reasons of climate and also health and biodiversity, CCUS could retain a limited role in industrial processes like cement.

4. NEGATIVE EMISSIONS TECHNOLOGIES (NET)

Methods and technologies: many complementary methods at small scales

from CCUS as they remove CO_2 after it has been released to the atmosphere. This has an obvious benefit that it can be done anywhere in the world, for example where land, water, energy, or geological storage is available. It also has a major drawback: CO_2 constitutes only 0.04% (420 ppm) of the atmosphere, compared to around 10% of the flue gas. As a result, the task is much harder (lower partial pressure, much more air flow per ton CO_2), and the process about 3-4 times more energy intensive.

This is also the reason why restoring or accelerating natural carbon cycles is generally more attractive than creating an entirely artificial process (see Figure 2).

Alternatively and more commonly (adapted from Minx et al 2018[8] and Fuss et al[20]), the wide range of NETs can be classified by type of capture and type of storage. Biological capture and storage is often referred to as Nature Based Solutions. Ocean fertilization is not included due to its very limited potential and numerous side-effects, altering physical, chemical and biological properties of marine ecosystems.

1. Biological capture and storage: photosynthesis captures CO_2, converts it to biomass, which can be directly stored, in several ways:
   - Reforestation or afforestation, storing carbon in trees: this is relatively easy and

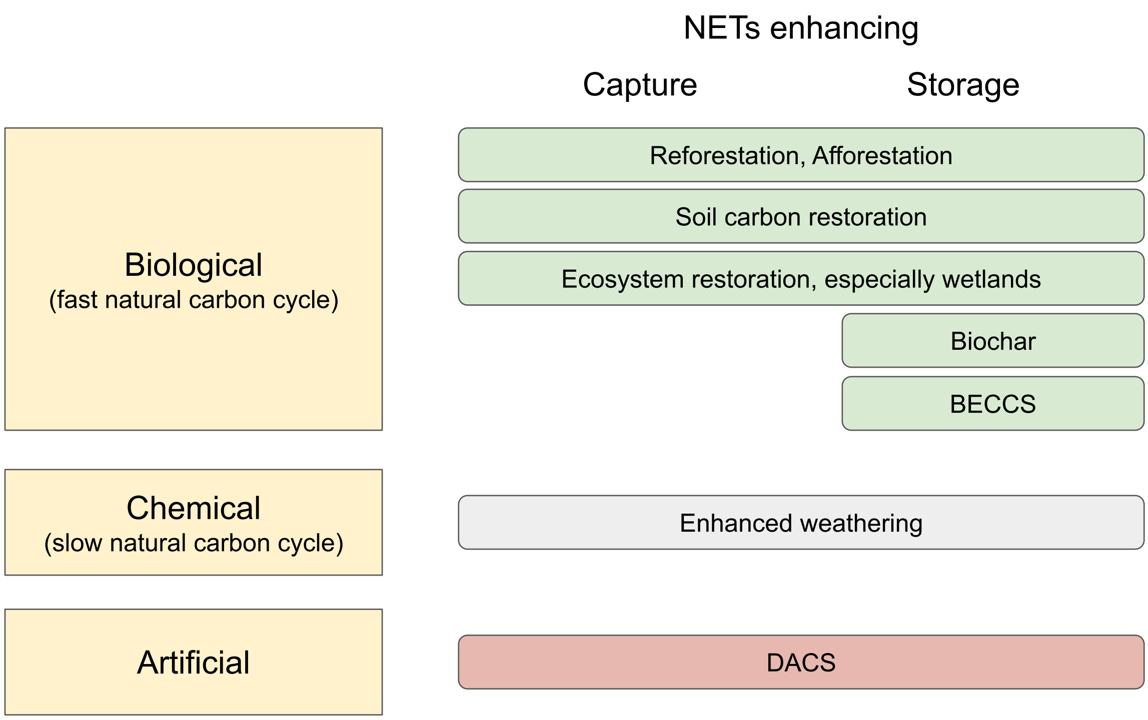

Fig. 2: Classification of NETs

mostly inexpensive, but requires a large land area. For example, capturing all current Swiss territorial emissions of 47 Mt CO_2e, using average young forests[21] at 6 tons/ha/year would need twice the total area of Switzerland, replanted every 20 years. Significant biodiversity benefits require "primary forests of native species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed"[22], which takes decades. This suggests a tradeoff between capturing CO_2, as young trees grow faster, and biodiversity, requiring old-growth forest. An additional difficulty is ensuring permanence, as forests could be cut down. They could also burn, quickly releasing the captured CO_2, which becomes likelier with a warmer climate and changed precipitation patterns.

- Restoring ecosystems, especially wetlands: this is one of the most promising climate actions. It is relatively easy and quick to reflood and stop further emissions from decaying peat biomass (flooding cuts oxygen flows). Within months, this generates significant biodiversity co-benefits, as wetlands tend to be "hotspots" of biodiversity. Reflooded wetlands immediately stop emitting and slowly start re-capturing the lost carbon, as plant matter accumulates over decades to centuries in wet, acidic and anoxic conditions. The main challenge is overcoming resistance, as most drained wetlands are productive agricultural land, due to rich organic soils. Worldwide, wetlands represent 3% of land area and store 30% of soil carbon (550 GtC). For Switzerland, of the 2500 km^2 wetlands in the early 1800s[23], well over 90% have been drained, with much of the rest degraded. The total potential of either avoided further emissions or recaptured carbon is not yet quantified, but decomposition of organic matter continues to emit thousands of tons of CO_2 per km^2 annually (typically 3500 t for organic soils used as cropland and 2000 t for the mineralization of drained raised bogs). These emissions alone probably reach millions of tons of CO_2 each year, and could be stopped rapidly and relatively easily.
- Soil restoration / soil carbon sequestration: soils naturally contain around 5% organic matter, about half of which is carbon, with significant local variations. Industrial agriculture degrades all components of soils, including the carbon content. Restoring soils naturally takes decades to centuries. Agroecology can help accelerate soil restoration, providing significant biodiversity co-benefits, but this is a complex undertaking, not yet fully quantified.
- Biochar: heating biomass without oxygen (pyrolysis) produces biochar, which is stable and can be stored for a long time, or applied to soils to help restore them, which improves both biodiversity and food production. The potential is limited by the quantity of available biomass. For Switzerland, see the biomass analysis in the BECCS section below.

2. Biological capture, geological storage: this method is also called bioenergy with carbon capture and storage (BECCS), and combines gasification or direct combustion of biomass for energy, with CCS, storing the resulting CO_2 underground. This works very well at small scale:
    - If limited to excess biomass and agricultural waste, and combined with biological storage described above, it remains limited in size but offers biodiversity co-benefits. In Switzerland the additional unused sustainable biomass potential is 2.6 Mt dry mass[24]. Reaching 80% of this potential, with 50% carbon in dry mass, we obtain BECCS potential of 2.6 Mt x 80% x 50% x 44/12 = 3.8 Mt CO_2 or 8% of 2020 Swiss

territorial emissions. On a lifecycle basis, 5-6% is more realistic.

- Trying to scale BECCS quickly becomes very problematic, as it requires much land and water to plant fast-growing biomass, competing with biodiversity (biodiversity needs old-growth forest, the opposite of fast-growing monocultures of young trees) and food (although this is more linked to our inefficient food system than to BECCS itself), very likely using fossil energy for the vast logistics required, and generating significant air pollution not captured by CCS.

3. Natural chemical capture and storage: this is the natural slow carbon cycle, which will remove all excess CO_2 from the air even if we do nothing, in thousands of years, through rock weathering, at a rate of 10-100 Mt C/yr. As we do not have so much time, we can accelerate this process:
    - Enhanced weathering is the name for all accelerated processes of grinding silicate and carbonate rock, or even recycled concrete. While the process effectively absorbs carbon, it could be hard to scale beyond just reducing emissions of recycled concrete, for lack of space to place the crushed rock, and the required energy. One ton of CO_2 may need around two tons of rock.

4. Artificial chemical capture, geological storage: also called direct air capture and storage (DAC or DACS). This process is similar to CCS, with several significant differences:
    - Geographical flexibility: DAC can be placed anywhere, for example in proximity to energy sources or geological storage formations.
    - Limited need for land and water.
    - Type of material used: typically solid sorbents using adsorption, i.e. capturing CO_2 on their surface (liquid solvents are also used, generally requiring high temperatures, and in hot and dry climates, a lot of water[25]). The process is relatively new, and the scale of facilities is much smaller than CCS, by a factor of 100-1000 per facility, as of 10-2021. Latest research however determines that sorbent or solvent consumption and manufacturing is not a limiting factor[26]. Hybrid approaches, like adsorbent+membrane, might be used in the future.
    - Energy use: this is by far the biggest issue, and most likely the fundamental limit of DAC. Due to the low concentration of CO_2 in the air at least 7 GJ is needed per ton; today the energy needed is closer to 10 GJ per ton CO_2.

In summary, many good and complementary methods for carbon removal exist, many of them with significant biodiversity co-benefits. A significant effort is needed to properly develop the knowledge, and then to widely build this capacity in society. The main issue is the possible scale, before the downsides predominate. From today's perspective, it looks difficult to remove more than a few percent of current emissions of 40 Gt/yr. This underlines even more the urgency of rapidly reducing emissions.

For Switzerland, all biological methods (Fig. 2) should be explored and implemented within the limits of available land and biomass, with focus on biodiversity co-benefits. Due to energy and land limitations, enhanced weathering will likely be limited to cement and concrete production; DACS is unlikely to scale (see next chapter).

Technical analysis of limits to NET

All NETs have fundamental limits, which are very different in nature:

1. Biological capture and storage: Overall land use, prevalent diets, agricultural practices, and food self-sufficiency; and more specifically:
    - Land area for forests and wetlands
    - Biomass for biochar

- Agricultural practice for soil carbon

2. Biological capture, geological storage (BECCS): availability of excess biomass and agricultural waste
   - Additional bottlenecks in the short term: geological storage, CO_2 transport, and methanisation
   - Note: the above limits apply to small-scale BECCS. Large-scale BECCS is much more problematic, see comment in previous section.
3. Natural chemical storage: land to place crushed rock, energy
   - Additional bottlenecks in the short term: integration with cement and concrete production
4. DACS: see analysis below

In summary, for the above methods 1-2-3, the fundamental constraint is land use, at a country and worldwide level, and interaction with / competition with food production, biodiversity preservation, and water use.

Direct air capture and storage (DACS): this is the most misunderstood NET method, as there are few absolute fundamental limits, and in theory tens of Gt CO2 per year could be captured and stored. In practice, DACS is likely to play a much smaller role in the decades critical for stabilizing the climate.

Our technical analysis is based on "Techno-economic assessment of CO_2 direct air capture plants"[25], one of the best-researched (optimistic) assessments of DACS, evaluating the feasibility of massive deployment, reaching 7-15 Gt CO_2 removed in 2050. The proposed analysis is based on technology learning curves, claiming that Gt-scale DAC is cost-feasible with early scale-up: "*CO_2 capture costs of LT DAC systems powered by hybrid PV-Wind-battery systems for Moroccan conditions and based on a conservative scenario, without/with utilisation of free waste heat are calculated at 222/133, 105/60, 69/40 and 54/32 €/tCO_2 in 2020, 2030, 2040 and 2050, respectively*". While the analysis is sound, we question the underlying fundamental assumptions:

1. Technology readiness: the paper[25], written in 2018, assumes total installed capacity of 1.5-3 Mt CO_2 p.a. in 2020. As of 11-2021, the global DAC capacity is well below 10 kt, or a factor of 2^8=256 lower than assumed, i.e. 8 doublings. Today there are no concrete plans to build 1 Mt DAC facilities, the standard size for large-scale deployment, which is again the same factor of 250x relative to the largest plant in operation. Clearly, we are not learning at the rate required for this scenario. The base case scenario implies the opening of one new functional 1 Mt DAC facility every week from 2020 to 2030, one every day from 2030 to 2040, and finally 3 per day from 2040 to 2050. As we still don't know how to build a single 1 Mt facility, this is highly ambitious. Even the conservative scenario, the basis for the final cost figures, assumes half this deployment rate (one Mt-scale facility every two weeks, two days, 16h in the 2020s, 2030s, 2040s, respectively).
2. Reliability of cost data: much initial cost data comes from a handful of DAC companies, generally secretive about their costs (their B2B contracts include a secrecy clause), with a strong incentive to account for their costs in the most favorable way, and no public audit. It is impossible to independently evaluate its reliability.
3. Shape of the learning curve: learning curves cover economies of scale, cost of inputs, experience of workers and managers, standardization, and discontinuities such as new product, process or technology. Every learning curve ultimately flattens out and may not be "well-behaved". Essential components of a DAC system such as PV, wind turbines, storage, fans, solvents, heat pumps will likely exhibit much lower capex reduction rates due to their large initial installed base, limiting DAC-induced doublings (see Ferioli et al. 2009 for a discussion of the component-learning hypothesis[27]). Large uncertainties must be expected due to

the very limited past scaling to date of DAC on which all cost data is based[28].

4. Scale of required energy system

a. Total DAC energy need: using the model developed in the paper (250 kWh-el + 1750 kWh-th per ton CO_2), for 15 Gt CO_2 we need 30 PWh energy, or when using a heat pump with COP of 3.5, a total of 11.25 PWh, or 40.5 EJ. This is almost half of today's global electricity generation (26 PWh) and 150% of the 2020 global renewable electricity generation (8 PWh). This does not count compression, transport, storage of CO_2, or conversion to synthetic fuels or feedstock.

b. Liquid fuel and feedstock estimate: liquid fuels contain around 45 MJ/kg; producing them from CO_2 and hydrogen needs at least twice this energy, typically 100 MJ/kg[29]. To convert 7 Gt CO_2 to liquid fuels, which are around 87% carbon, we obtain 7 Gt * 12/44 / 0.87 = 2.2 Gt fuels. This requires around 220 EJ energy, which is much more than the DAC alone (but includes DAC for the portion converted to fuels).

c. Battery storage: to ensure 8000 h/year operation needed due to high capex, battery electricity storage covers 56% of total energy, i.e. 40.5 EJ / 365 * 56% = 62 PJ or 17.26 TWh. This represents around 86 Mt of batteries (200 Wh/kg) or 4.3 Mt of lithium (250 g li/kWh), around 50 times the 2020 world lithium production.

d. Waste heat: given the total thermal energy needed of almost 100 EJ, this probably exceeds the expected world waste heat in 2050, assuming improved energy efficiency and therefore less waste heat. This would make the second set of cost figures unlikely (222/133, 105/60, 69/40 and 54/32 €/tCO_2 in 2020, 2030, 2040 and 2050, respectively).

Building on the results of this detailed model[25], we have shown several fundamental reasons why optimism about DACS seems misplaced, in particular the learning curve potential and energy constraints. Without trying to predict the future, it calls for caution about the prospects of Gt-scale DACS in the next 3-4 climate-critical decades.

5. COSTS AND FINANCING

Cost overview

Almost every aspect of removing CO_2 discussed above is difficult, for different principal reasons:

- Energy use, loss of efficiency, cost
  - Post-combustion CCS requires separating CO_2 from other flue gases, starting from a low partial pressure, and requires compression and filtering.
  - Oxyfuel and pre-combustion CCS simplify separation by adding costly and complex processes to transform the combustion medium or fuel.
- Land use, need to reform agriculture, cost
  - Restoring wetlands is relatively easy as it generally just needs re-flooding. If polluted, de-pollution is a slow, expensive process. However, many ex-wetlands are today productive agricultural land, requiring significant change in agricultural practices.
  - Billions of years of evolution have made photosynthesis very resilient. Yet it is inefficient, converting only 1-2% of solar to chemical energy. This leads to very high requirements for land, water, nutrients, and competes with other land use, especially agriculture as practiced today, limiting the potential of all biological capture and storage methods. This in no way diminishes the importance of biological methods, just means they will not remove more than a few percent of today's emissions.
- Engineering challenges, time to deploy, cost
  - Almost no industrial sites are equipped today with CCS. Many could be retrofitted, at significant cost.
  - Compressing and transporting CO_2 requires infrastructure, energy, and has to overcome corrosiveness and risk of potentially dangerous leakage.
  - Storing CO_2 in geological formations requires the development of suitable sites, which takes years to well over a decade and needs careful and constant monitoring. Often the sites are far from emission sources, making transport more expensive and complex.
  - BECCS is based on expensive methanisation, or highly polluting biomass burning, requiring filtering.
  - Collecting and transporting biomass at scale must be done without fossil fuels. Almost no such infrastructure exists today.
  - Very little pyrolysis capacity for making biochar exists today.

Unsurprisingly, carbon removal is expensive[8], with the exception of some biological methods:

- Reforestation or afforestation is the only inexpensive method, usually well below \$100 per ton CO_2
- Soil carbon, depending on method <\$100/t
- Biochar, \$8-300/t
- BECCS, \$45-250/t
- DACS, around \$1000/t in 2021, expected to fall slowly (EU REF2020[30] estimates €894 in 2030, and €595 ultimate); see also "Technical analysis of limits to NET"
- Enhanced weathering, \$40-1000/t

As carbon removal grows in scale, it will simultaneously experience two opposite cost effects:

- Costs will *fall* with scale, this is the learning curve: technical methods become less expensive over time, methods improve, standards emerge, people are trained, etc.
- Costs will *increase* with scale, as the project portfolio changes. Lowest-cost projects get

funded first, for example: most accessible biomass, easiest to develop geological storage, most suitable / unpolluted ecosystems to restore. With growing scale, higher-cost projects must be added.

The first effect, learning curve related cost reduction, can be quantified based on experience. The Global CCS Institute estimates scaling costs[14] of CCS, relative to the size of the plant:

capture_cost_index = scaling_factor^{n-1}
At constant CO_2 partial pressure, n is typically 0.6 (single plant) to 0.8 (multiple plants)

For Switzerland, this means for example:

- Scaling from 100 to 500 kt CO_2 reduces capture cost by 47%: $1 - 5^{0.6-1}$ (from incineration to cement plant)
- Scaling from 1 to 20 point sources reduces capture cost by 45%: $1 - 20^{0.8-1}$ (from 1 to 20 incinerators)

This is consistent with the only detailed Swiss CCS cost estimate, for the KVA Linth incinerator, by ETHZ Sus.Lab[31], estimating initial single-plant operation at CHF 156-190/t CO_2, and scaling potential to reduce this cost to CHF 68-108/t.

This may be optimistic, as it assumes sufficient scaling of Norwegian geological storage. Once we reach Mt-scale CCS in Switzerland, the storage may need to be domestic, to avoid international transport and storage bottlenecks, adding uncertainty to future costs.

Financial incentives

CO_2 capture is costly, whether it is through capture at the smokestack or a NET, a cost that cannot be covered by selling the CO_2. The fundamental reason is that CO_2 is a stable molecule, with very limited use as such (carbonated drinks, greenhouses). For any other use, as material or fuel, the strong bonds between carbon and oxygen need to be broken, at great energy cost, in complex processes, using expensive equipment. Furthermore, using the CO_2 would result in its ultimate release into the atmosphere. This would be at best neutral, if it replaces fossil CO_2.

Compressing, transporting, and permanently storing the CO_2 captured at the smokestack or through a NET further increases the costs. The options for covering the capture and storage costs differ between CCS and NETs.

CCS is implemented by a CO_2 emitter as a means to reduce his CO_2 emissions. Therefore, the incentives for emission reductions could contribute to covering the costs of CCS. The implications for global net emissions depend on the type of mitigation incentive chosen:

1. Tax or subsidy on CO_2 emissions. The emitter gets the costs of CCS covered if the tax avoided or the subsidy earned exceed these costs. He selects the CCS option only if he does not have cheaper means to reduce his emissions. In that case, CCS is a net reduction of global emissions.
2. Emission rights (cap-and-trade). If the emitter is endowed with an allocation of emission rights, CCS saves him a quantity of these rights that he can sell. If he gets no endowment or a too small one, CCS dispenses him from buying emissions rights. The emitter gets the costs of CCS covered if the market price of the emission rights exceeds the costs of CCS. As the emission rights not bought thanks to CCS or sold will be used by another emitter, CCS does not lead to a net reduction of global emissions under a cap-and-trade regime.
3. Specific subsidy. A subsidy for setting up and operating CCS could, of course, encourage the CO_2 emitter to adopt this solution if it covers the full cost. In case of partial cost coverage, the subsidy must be complemented with other mitigation incentives.

Thus, CCS leads to a net reduction of CO_2 emissions if the emitter is granted a subsidy or exposed to a CO_2 tax that induces him to adopt this technology and to reduce thereby his emissions beyond the level he would have chosen to abate through other mitigation options.

A NET is usually operated by an operator who does not emit much CO_2. His costs can be covered through these instruments:

1. Voluntary compensation. A CO_2 emitter pays for the NET because he wishes to be carbon neutral from an accounting point of view. In this case, the NET offsets emissions which otherwise would not have been abated.
2. Legal compensation. A CO_2 emitter pays for the NET, the quantity of CO_2 captured being subtracted from his own emissions with a view to meeting a mitigation target or avoiding the purchase of emission rights. As the NET offsets emissions which otherwise would have been abated, it does not contribute to a net reduction of the CO_2 emissions.
3. Emission rights. The NET operator is granted emission rights per tons of CO_2 removed from the atmosphere. He can then sell the permits to cover his costs. In this case, the NET does not contribute to reducing total emissions under the "bubble" created by the cap-and-trade system, as it simply allows another emitter to emit more CO_2, the emitter who buys the permits from the NET operator.
4. Subsidy. The NET operator is paid a subsidy for setting up and operating the system or per ton of CO_2 removed from the atmosphere. In this case, the NET leads to an actual reduction of the CO_2 concentration in the atmosphere.

Thus, NETs only lead to an actual reduction of the CO_2 concentration in the atmosphere when they are paid for through subsidies, or are voluntary.

Under the polluter pays principle, the financial resources for the subsidy should be provided by CO_2 emitters, past or present. Raising these contributions pro rata of their CO_2 emissions would provide them with an additional incentive to reduce these emissions. Furthermore, the quantity of CO_2 extracted from the atmosphere thanks to the subsidy they make possible could be interpreted as an offset for their emissions.

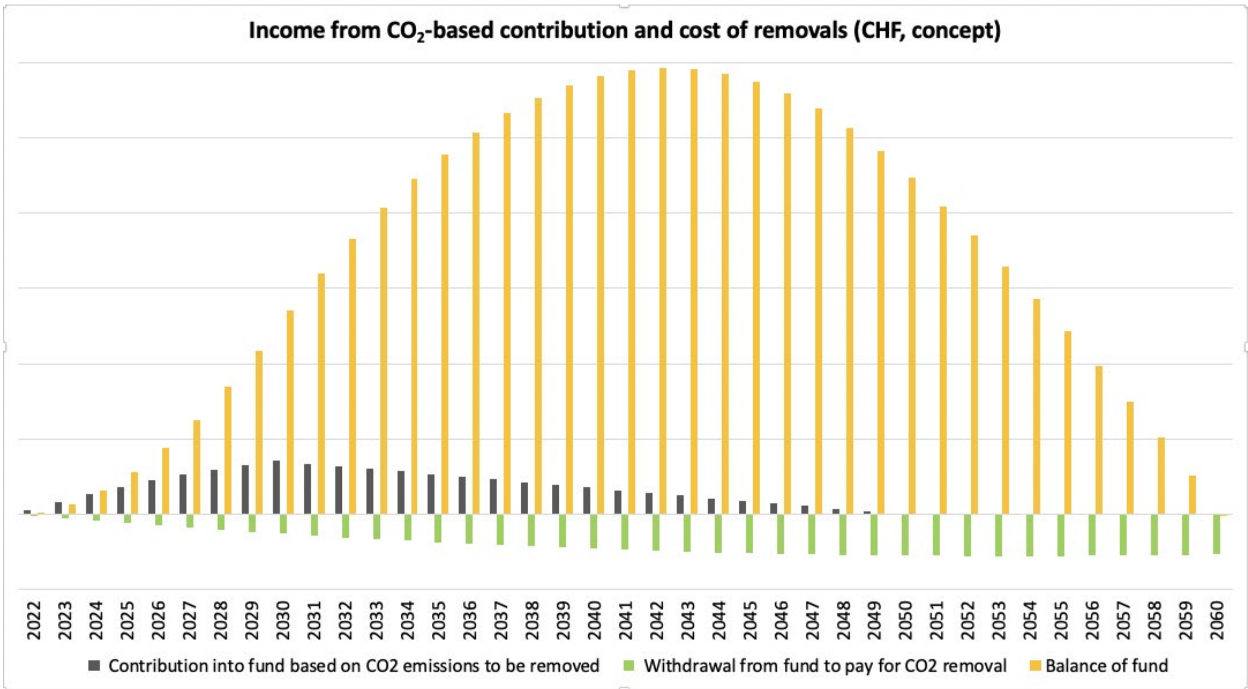

Fig. 3: Example of separating revenues from removal projects via a climate cleanup fund

Disconnecting polluter payment from clean-up costs

Given the high cost of NETs, the proportion of CO_2 emissions offset through them and the timing of these offsets is critical. Consider this thought experiment. Suppose that NETs could be deployed on a large scale as soon as 2023 at an average cost of CHF 500 per ton of CO_2 permanently removed from the atmosphere. If 100% offset were the goal, a contribution of CHF 500 would have to be levied on every ton of CO_2 emitted in 2023. This would be a huge burden. Furthermore, as time passes the cost of NETs decreases but so do the emissions of CO_2. Some time between 2040 and 2050, CO_2 emissions would be down to zero, so there would be no base any more for financing the subsidy for NETs, precisely when they could extract CO_2 at much reduced costs.

It is, therefore, preferable to disconnect the collection of the contribution and the payment of removal costs. This can be achieved through a fund, such as the Swiss Climate Cleanup Fund proposed in the E4S working paper "*Climate Cleanup Fund - getting to Swiss Net Zero*". How this could work is illustrated in Fig. 3. In this illustrative example, the emitter pays a constant fee of CHF 200 per ton CO_2 emitted into the fund. These payments decrease together with the volume of emissions, to reach zero in 2050. In 2022, when removal costs CHF 500 per ton, only 1% of that year's emissions are removed. The expense is withdrawn from the fund. As removal costs decrease, the volume of CO_2 removed increases, up to its maximum in 2060, when it is over 50 times the volume removed in 2022. Between 2022 and 2060, all emissions accumulated between 2022 and 2050 have been removed at a cumulated cost that is equal to the total amount of contributions into the fund (with interest added).

Finally and crucially, the fund mechanism is self-correcting, as the carbon price will be highly dependent on the speed of decarbonization. In any given year, there is a portfolio of available carbon removal projects, with very different costs per ton. The lowest-cost projects get funded first, and the average price will be strongly dependent on the volume: fast decarbonization will leave little residual emissions, and a low average removal prices. If decarbonization is slow, carbon removal volume will be high, with a very high average price. This will create a strong incentive to decarbonize faster.

6. STRATEGY AND IMPLICATIONS

The case for planning CCS+NET together

Conceptually, CCS and NET are very different, as the first reduces emissions, and the second removes CO_2 from the atmosphere. However, there is a strong case to analyze CCS and NET together, for the following reasons:

- Many technologies or non-tech systems are shared: carbon capture (fossil CCS and BECCS), CO_2 pipelines, geological storage, as well as monitoring, financing, reporting, and governance.
- CCS is needed short-term, while we still burn fossil fuels, but has little long-term potential beyond cement. Building the infrastructure becomes more feasible if later used for BECCS. In case of constrained availability of shared infrastructure, a common perspective is essential.
- CCS and NET might work best if they share the same policy instruments, for example a price for emitting or credit for removing CO_2, or a mandate to remove all emissions.

Geopolitical conditions for deployment

There is a big difference between:

1. Biological capture and storage (reforestation, ecosystem restoration, soil carbon, biochar), where the carbon storage is either a living part of biodiversity (trees, wetlands) or a major contributing factor (carbon-rich soils),
2. BECCS, if limited to excess biomass and agricultural waste, with no adverse biodiversity effects, and
3. Other methods, such as CCS or DACS

if properly designed and managed, and limited in scale (see §4 NET), the first helps biodiversity (and resilience, ecosystem services, climate adaptation), the second generates electricity and heat, and the third has no co-benefits beyond removing carbon, especially no local co-benefits.

Therefore the first two may work if supported in the local context. Due to the absence of co-benefits of CCS or DACS, other than removing CO_2 from the atmosphere, they require an almost perfect global coordination. Even a 20-25% leakage, i.e. a quarter of the world continuing to emit CO_2 unabated, would completely negate the whole effort: assuming the “climate action world”, accounting for 80% of 2020 emissions, decarbonized according to IPCC SR15[1] and reduced emissions by 90%, the “no climate action world” would account for over ⅔ of global emissions - in this case carbon removal in the first group would be just as costly but would have little impact. At a minimum, this coordination would cover restricting emissions, regulating CO_2 transport and sequestration, and financing CCS and NETs. This is much harder than accelerating existing approaches such as the Paris Agreement NDCs, CBAM, carbon taxes and regulation, and financing CO_2 removal with local biodiversity or societal co-benefits, which can all be effective at the regional scale or in partial coalitions (“climate clubs”).

The Carnegie Climate Governance Initiative[32] (C2G) provides a good overview of carbon removal governance, and the numerous remaining gaps.

In particular proponents of massive DACS[25] sometimes mention the theoretical scenario where we wait so long that nothing other than multi-Gt-scale DACS works. This is particularly unlikely - if ecosystem services start to collapse, leading to widespread hunger, migration, conflicts, and possibly war, coordinated global action towards long-term goals becomes even more difficult. Unilateral, uncoordinated SRM could be a more likely outcome.

Purpose of carbon removal

Let us restate the main purpose of carbon removal: help reach net zero by removing the residual emissions, after sufficiently deep decarbonization. Longer term, beyond reaching net zero, carbon removal could progressively reduce the CO_2 concentration. However, the urgency remains to reach net zero by 2050 latest[1].

As this includes CCS and NET, there could be a scenario where rapid deployment of CCS alone reaches 10-15% of 2020 emissions, before declining due to the required phase-out of fossil fuels for health and ecosystem reasons. However, the high costs, difficulty of reaching the almost perfect geopolitical coordination needed (see above), and the fact this huge transformation of society would be useful for perhaps only 2-3 decades, makes this rather unlikely.

Additionally, the goal is to provide real biodiversity co-benefits, and generate electricity and heat (BECCS).

This is not at all how CCS developed historically: to extract more oil from depleted fields. It is also not why major players today show their enthusiasm for CCS, and confidence in future NETs: to extend the fossil era, prolong the lifetime of stranded assets like coal power plants, open new markets for oil companies (CCS solvents), or simply benefit from many available "green" subsidies. Stabilizing the climate is conspicuously missing from the goals of almost all main players.

As carbon removal is essential, it is urgent to set the right priorities and policies. Otherwise, it will remain a transfer of wealth from taxpayers to corporations, and not help stabilize the climate.

As the Economist[33] wrote just before COP26 opened: "*One problem is that fossil-fuel industries and governments that value them have an interest in saying they are pursuing CCS, because it seems to provide a future for some fossil fuels, but no pressing reason to make it an implemented reality. The technology makes plants more expensive and less efficient, and in the absence of a high carbon price that is a penalty nobody wants to pay*".

Global moral hazard?

Moral hazard in economics is a situation when an organization has an incentive to take too much risk because it is not fully liable for the consequences.

Moral hazard related to carbon removal could occur if it limited or delayed emission reductions[34].

As argued in this paper, the moral hazard can be significantly reduced if carbon removal is seen as a method to remove residual emissions only, assuming the deep decarbonization pathway is reasonably well defined. It is especially important to define the timeline and sequence of activities scheduled for fossil fuel exit, and the "acceptable" residual emissions for other sectors like cement or agriculture. Lacking clear pathways, many sectors could consider their own emissions "unavoidable", and part of the last 10%.

Successful initial deployment of CCS or NET with rapidly falling costs could also create a moral hazard, reducing the pressure to decarbonize rapidly, creating an incentive to invest even more in carbon removal, making it the single point of failure of climate policy. Such failure could materialize due to an unforeseen barrier or simply flattening of the learning curve (see "Technical analysis of limits to NET" above), leaving the world dangerously unprepared for the climate emergency.

Social acceptance

In this new field, public perception is constantly evolving, and much depends on how questions are framed. The UK Climate Assembly, comprising 108 randomly selected citizens using stratified sortition and thus representative of society, deliberated between January and May 2020, to determine how the UK could reach net zero. The final report[35] specifically includes carbon removal, with 4 measures broadly accepted (reforestation and better forest management, restoring wetlands, using wood in construction, and enhancing soil carbon), and two very divisive measures (BECCS and DACS). The concern for the last two methods were related to:

- Potential leaks from geological storage
- Failing to address the problem, distracting from emission reductions
- Less natural, costly and unproven, for DACS also "needs a lot of energy"

Very interestingly, UK Climate Assembly members also said that BECCS and DACS "*should only be used in moderation as a way of capturing that last bit of carbon that can't be captured by a combination of natural methods of carbon storage and moves towards generating carbon neutral energy*". Additionally, fossil energy with CCS was strongly rejected as a pathway to low-carbon electricity, much more than BECCS and DACS.

Energy limits and alternative uses

Fossil fuels still account for well over 80% of the almost 600 EJ annual world primary energy consumption[36]. Rapidly exiting fossil energy is a climate, biodiversity, health and ethical imperative. Retrofitting CCS to coal and gas power plants benefits the climate but increases non-CO_2 pollutants, due to higher fuel consumption, hurting the most vulnerable ecosystems and people. It also extends the fossil age. Replacing these 500 EJ with clean energy will be a colossal task, making energy constrained for decades to come, very likely at levels below today's 600 EJ total.

In this context, which uses of this precious available clean energy will lead to the highest level of human wellbeing? This question is of course worth asking for many activities. Given the energy intensity and scale needed for carbon removal, it is particularly important for DACS and synthetic fuels.

On average, each human uses 63 GJ of fossil energy per year, emitting 4.8 t CO_2. Removing this CO2 using DACS requires around 48 GJ not counting compression, transport and storage, which is around ¾ of the primary energy and 100% of final energy generated by burning this fossil fuel. Replacing this fossil by DACS and synthetic fuels (a form of CCU, where the carbon is re-emitted within weeks) would require at least 150 GJ clean energy per person per year (see Scale of energy system in Technical analysis of limits to NET). This is a quantity of energy unlikely to be available for a very long time, and around 10 times the energy needed to satisfy all human needs[10].

In perspective, 15 GJ of clean energy can power energy services to satisfy the annual needs of one person. Or it could sequester 1.5 tons of CO_2 using DACS, a third of their emissions. Alternatively, it can produce around 6 GJ synthetic fuel or 130 kg, corresponding to 1/10 of their current use.

There are many good reasons to develop clean energy as quickly as possible. Still, in an energy-constrained world, at any given point, surely the highest priority must be universal access to basic energy services. Rapidly exiting fossil fuels, building renewables, and ensuring inclusivity are already highly ambitious. Simultaneously doubling or tripling the energy system to provide for DACS and synthetic fuels at scale is highly unlikely.

Potential limits to carbon removal

Are there hard, physical limits to carbon removal? Yes, but too far to be of practical importance in the coming decades or even centuries. Incoming solar radiation on Earth is limited; this energy has many other essential uses. Regardless of the energy source, any energy conversion generates waste heat, which will, at sufficient scale, heat the planet. On the other hand, geological storage is probably sufficient to store all the world's carbon.

In the coming decades, essential for stabilizing the climate[1], the main constraint are ecosystem services. Do we optimize BECCS for yield by planting high-growth monoculture, or for biodiversity and resilience, giving the primary forest the long time it needs to grow, slowly capturing carbon? How do we transform our food system for health, sustainability and resilience, so it complements carbon removal, not competing with it? For optimal soil health, how much crop biomass can we remove, while reducing chemical fertilisers?

The size of CCS is limited by suitable point sources, which will all sooner or later move away from fossil fuels. This limits the time window during which CCS operates, and unless potentially converted to BECCS, makes it harder to finance. Constrained energy supply might change our priorities, as argued in the previous section.

The IIASA ENGAGE[37,38] project analyzes "net-negative" scenarios with slow decarbonization and massive carbon removal later this century, showing "hazardous levels of overshoot". Limiting this warming overshoot requires faster decarbonization, and ultimately less need for carbon removal, as in IPCC 1.5°C pathways P1 and P2[1].

Finally, it will take time to learn: refine methods, train people, develop monitoring and governance, share best practices, standardise key components and their production, create the needed geopolitical conditions for deployment, structure financing and raise money. CCS has decades of experience in EOR; now we have a completely different challenge and little experience.

Given the extraordinary complexity and all these moving parts, we are not aware of any suitable complete model, beyond the estimates of afforestation and BECCS used in IAMs. So it would be hard to model, much less prove, our estimate that carbon removal is unlikely to exceed 5-10% of current emissions. We do, however, show the estimates for Switzerland, which are consistent with this level. At a worldwide level, this remains an ongoing effort; IPCC AR6 WG3 will provide a new estimate.

The remaining open questions of detail should not delay urgent climate action, and carbon removal is clearly one of several good 10% solutions. It must not be seen as the solution to the climate crisis.

Implications for Switzerland

What does this mean for Switzerland? Switzerland has a few specificities, each with their own implication (→):

- Rich but fragile ecosystems, partly high altitude, stressed by industrial agriculture, already exposed to 2°C warming
  - → Importance of measures with biodiversity co-benefits, especially ecosystem restoration and biochar / soil carbon projects.
- Small size, high density: biomass very limited, multiple competing uses
  - → Strong limitation of the total potential of carbon removal for reforestation, ecosystem restoration, biochar, or BECCS, highlighting the importance of rapid and deep decarbonization.
- Geological structure conducive to permanent storage in saline aquifers unexplored, only theoretical assessments available. Landlocked country with no significant storage in neighboring countries
  - → Urgency to explore domestic geological storage, even more so given the long lead times.
- Significant short-term CCS potential from cement, chemical plants and waste incineration
  - → This potential can be exploited at scale only if domestic geological storage is developed rapidly. It is likely that deep decarbonization will significantly reduce the potential of CCS, perhaps after 20-30 years.
- Growing acceptance of the idea of equipping waste incinerators with CCS
  - → As about half of incinerated waste is wood and other biomass, this part would count as NET (BECCS). BECCS provides a way to extend the lifetime of shared CCS infrastructure: storage, transport, and capture, at least in waste incineration.

- No suitable energy sources for DACS at any meaningful scale
    - → DACS unlikely to scale in Switzerland.
- Significant imports of embodied emissions, ⅔ of the total[39]
    - → In a logic where carbon removal follows emissions, probably only territorial emissions could be removed domestically. Deep decarbonization will very probably completely reconfigure the value chain, so these proportions may change.

The Swiss potential carbon removal, costs and a financing mechanism are developed in the E4S working paper "*Climate Cleanup Fund - getting to Swiss Net Zero*".

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