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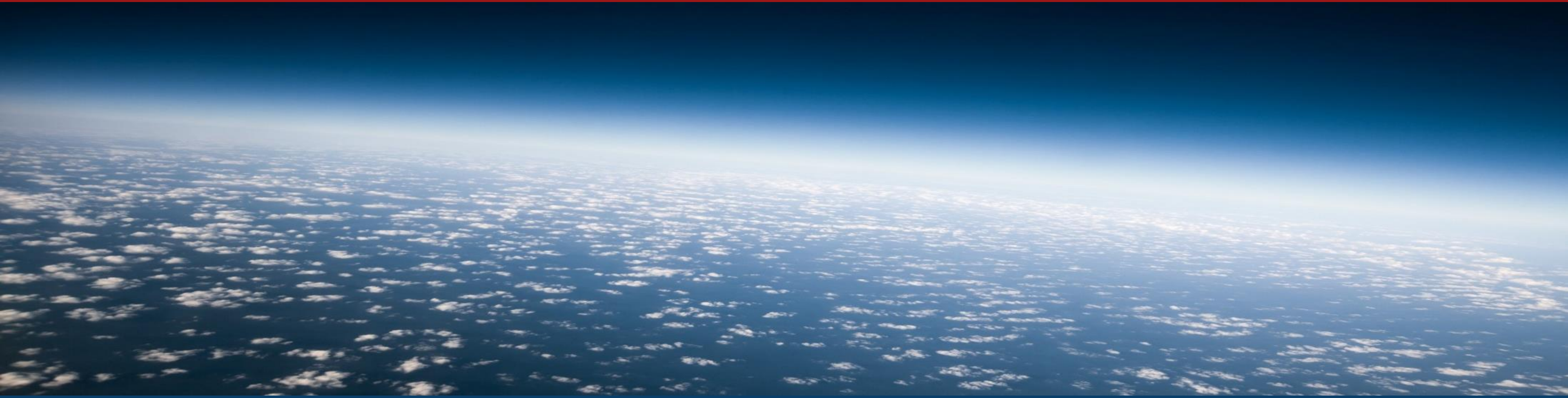

Toward a Carbon-Free World

Negative Emissions Technologies

A.T. Kearney Energy Transition Institute
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Compiled by the A.T. Kearney Energy Transition Institute

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About the FactBook: Negative Emission Technologies
This FactBook seeks to summarize the status of the negative emissions technologies and their prospects, list the main technological hurdles and principal areas for research and development, and analyze the economics of this space.

About the A.T. Kearney Energy Transition Institute
The A.T. Kearney Energy Transition Institute is a nonprofit organization that provides leading insights on global trends in energy transition, technologies, and strategic implications for private-sector businesses and public-sector institutions. The Institute is dedicated to combining objective technological insights with economical perspectives to define the consequences and opportunities for decision-makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

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Negative emission technologies are a necessary support of land and oceans into removing CO_2 from the atmosphere

- Anthropogenic CO_2 emissions have accelerated during the 20th century with global CO_2 atmospheric concentration reaching 411 ppm in February 2019 (by far the highest level over at least the past 400,000 years). According to the Intergovernmental Panel on Climate Change (IPCC), current **global warming scenarios are still above the 2°C target** of the 2015 United Nations Climate Change Conference (COP21), and even a 1.5°C warming would lead to dramatic consequences on ecosystems and societies.
- Anthropogenic CO_2 emissions of about 40 $GtCO_2$ per year contribute to the global carbon cycle that stores carbon (equivalent to ~171,000 $GtCO_2$) in various forms and describes multiple fluxes between oceans, land, and the atmosphere. The consumption of fossil fuels since the beginning of the industrial era has not only largely contributed to increase the quantity of carbon circulating each year, but also generated imbalance fluxes, leading to a **~30% increase of the atmospheric carbon stock** from 1750 to 2011. Global carbon cycles involve complex exchange mechanisms and various natural reservoirs. Their understanding is therefore fundamental to predict the evolution of the atmospheric CO_2 concentration:
  - **Oceans store about 87% of total carbon on Earth.** Carbon in the oceans is unevenly distributed and mostly stored in the surface oceans (mass of carbon equivalent to ~3,000 $GtCO_2$, mostly in the form of dissolved inorganic carbon), with a residence time of 1 to 10 years and in the intermediate and deep sea (mass of carbon equivalent to ~136,000 $GtCO_2$), with a residence time of 200 to 1,000 years. Thus, the oceans' capacity to absorb CO_2 depends on its ability to transport the carbon in the surface waters to the intermediate and deep sea. Four natural mechanisms are responsible for this transport, but climate change is threatening to reduce their strength. With an uptake of 8.8 $GtCO_2$ per year and recently increasing 22% per decade, **oceans are still net absorbers, despite emitting in warm tropical regions.**
  - **Land represents 9% of global carbon storage.** Land storage is predominant in tropical and boreal regions. Despite soils and permafrost storing an equivalent of ~13,000 $GtCO_2$, the ~2,000 $GtCO_2$ in vegetation are responsible for the biggest fluxes (about 451.4 $GtCO_2$ per year). Photosynthesis(+) and respiration(-) leave a positive uptake of about 48.4 $GtCO_2$ per year, which is later reduced to 6.2 $GtCO_2$ per year by natural processes and human activity. Although models suggest the land carbon uptake has been growing, these models have high uncertainties, and climate change is predicted to diminish the land's ability to store carbon.
  - **Atmosphere represents about 2% of global carbon storage** but plays a central role as it interacts with all other reservoirs.
- The continuous increase in atmospheric carbon of 17.2 $GtCO_2$ per year on average in the 2008 to 2017 period confirms that land and oceanic uptakes cannot counterbalance anthropogenic CO_2 emissions. CO_2 concentration rose from 385 ppm to 411 ppm over the past decade, getting closer to the 450 ppm threshold of the 2°C scenario.
- Since CO_2 represents about 75% of yearly anthropogenic greenhouse gas emissions, it is the main focus of solutions policies. According to the IPCC, keeping global warming below +1.5°C would require negative emission technologies to capture 3.1 to 14.9 $GtCO_2$ per year on average until 2100, depending on the evolution of global CO_2 emissions.

Ten types of NETs are being developed, enhancing natural phenomenon or creating new engineered processes

- Multiple strategic options have been debated for mitigating the impact of climate change. The ones studied in this FactBook, negative emission technologies (NETs), can be classified as either natural processes enhancement or engineered processes. NETs differ from zero-emission solutions because their overall carbon balance is negative, not neutral.
- **Afforestation and reforestation** are the most well-known NETs. They are already being implemented on a large scale, particularly in China, but must be drastically increased and optimized to match the targets. Its potential is important, between **0.5 and 3.6 Gt-CO_2** removed per year, with some authors suggesting even higher values, at a relatively **low cost**, $5 to $50 per t-$CO_2$ and without energy requirements. Afforestation and reforestation are limited by land and water use, in competition with food supply and bioenergy. By organizing long-term **forest management**, significant profits could be earned by cutting trees at the optimum time to maximize carbon removal rate and by using the organic material resulting for wood products, bioenergy with carbon capture and storage, biochar or long-term sequestration in the oceans.
- **Oceans**, the biggest carbon reservoir, can capture carbon in multiple ways. First, storing biomass (such as crop waste) underwater can be a cheap and effective solution to prevent re-emission from burning or decomposition **(CROPS)**[1]. Second, **boosting phytoplankton activity** by adding nutrients in oceans is another solution that offers an astounding potential—from 2.6 to 6.2 Gt-CO_2 per year at a limited cost of between $23 and $111 per t-$CO_2$. However, this process called **ocean fertilization** seems complicated to implement because of unknown potential risks for ecosystem and problems linked to oceans property. Third, **artificial upwelling** could offer another possibility by pumping nutrient-rich water from the sub-surface ocean to the surface, but this remains theoretical and risky because of a lack of knowledge. Finally, **ocean alkalinity enhancement** consists of adding alkaline materials to sea water. This has a big potential of carbon capture (2 to 20 Gt-CO_2 per year) while fighting ocean acidification. Yet, cost is still undetermined ($10 to $600 per t-$CO_2$). **The technologies involving oceans have great potential, but all of them are in incipient stages.**
- Land is a smaller reservoir than oceans but offers possibilities to capture more carbon than it already does. Weathering is the natural process of rock decomposition via chemical and physical processes in which CO_2 is spontaneously consumed. This process can be enhanced by augmenting the surface area of the rock exposed, and the most pragmatic approach is considered to be spreading fine-grained rock dust over croplands, which also has co-benefits for agriculture. The potential of this solution is 2 to 4 GtCO_2 per year, at a cost of $50 to $200 per t-$CO_2$. Another solution is to increase **soil carbon sequestration:** Several soil management practices could have a 20-year potential from 2.3 to 5 Gt-CO_2 per year. Because of co-benefits in agriculture such as reducing erosion and improving soil fertility, costs could even be negative, ranging from -$45 to $100 per t-$CO_2$.

1. CROPS is crop residue ocean permanent sequestration.

NETs could have the potential to meet the IPCC target, but most are far from maturity and have to prove their scalability

- **Bioenergy** is usually considered carbon neutral, but it can be carbon negative when coupled with **biochar** stored in the soil or with carbon capture and storage **(CCS)**. Biochar allows capturing carbon and producing energy at the same time. However, it is constrained by cost penalties because of **pyrolysis efficiency** and avoided energy production with charcoal burning. It could be partly balanced by biochar fertilizer effect. CCS used in the framework of bioenergy is already operable and has a significant potential of 0.5 to 5 Gt-CO_2 per year. As referred in our CCS FactBook, the technology is mature and promising, but cost penalties curb its progress. NETs relative to bioenergy offer amazing perspectives but are harshly limited by a huge **competition on the energy market, land-use and water consumption**. Studies are trying to boost photosynthesis efficiency, which could be profitable for the bioenergy sector in a hypothetical future.
- **Direct air capture (DAC)** represents a set of technologies that can capture CO_2 directly in ambient air to store it or use it. DAC avoids or at least reduces transport fees because it can be built on the CO_2 utilization or storage site. However , **low concentration of** CO_2 in ambient air makes it less efficient and costlier than CCS. Few companies have launched pilot plants or small-scale commercial plants, which already capture up to 1 Mt-CO_2 per year. These companies are currently working on reducing costs through innovation and deployment. Although they currently supply only the food and beverage industry, they seek to create and enhance revenues by sales in order to provide CO_2 for EOR and carbon-to-products, making them carbon negative in the future.
- Each brand develops its own DAC technology. All of them have a collector, a chemical agent that reacts with ambient CO_2, and a chemical agent regeneration to reuse the chemical agent while providing CO_2. Active collectors are sets of fans designed to blow air until the chemical agent. They consume electrical energy (150 to 450 kWh per t-CO_2), while passive collectors exploit natural wind to move air across the chemical agent. Temperature-swing adsorption consumes thermal energy (4 to 9 GJ per t-CO_2), whereas moisture-swing adsorption seems to be less consuming (1.1 GJ per t-CO_2 for the Center for Negative Carbon Emissions, or CNCE) but requires more water. **Climeworks, Carbon Engineering,** and **Global Thermostat**, the three most advanced technologies, are using active collectors and temperature-swing adsorption, which make them energy consuming and relatively expensive. The **CNCE** solution, which is still a lab work, operates with a passive collector and a moisture-swing adsorption, making it very energy efficient but requiring 5 to 15 tons of water per ton of CO_2 captured.
- DAC is very efficient in terms of land use, approximatively 100 to 400 times more than forests. Despite its cost, which remains high mainly because of energy consumption, DAC has a massive potential and could have a crucial impact on carbon concentration with more advanced technologies. Indeed, DAC is theoretically only constrained by geological storage capacity.
- Even if commercial projects are already operating, most NET development at large scale (in the range of 1 Gt-CO_2 per year) is still theorical and would benefit from higher carbon prices or a subsidy policy.

Some NETs could offer huge new business opportunities, yet they would require strong policy support and technology improvements

- In the **COP21**, signatories of the **Paris Agreement** agreed to follow a set of submitted **National Determined Contributions** (NDCs). Although countries' NDCs refer to net emission reductions (possibly contemplating NETs), only afforestation and reforestation are mentioned so far, in a way that is difficult to quantify globally. In 2017, the United Nations set global forestry goals that could capture between **1.6 and 3.8 $GtCO_2$ per year.** These values are not only speculative, but also subject to reversal and even if they become true, they would only potentially meet IPCC's pathway P1 necessary carbon capture values. Multi-billion dollar reforestation and afforestation initiatives in Africa, South America, China, and India will be responsible for capturing between 1.74 and 2.6 $GtCO_2$ per year, yet there are many challenges to the efficacy and transparency of all these programs.
- **Investments in other NET remain minor** because most projects lack a solid business plan. The investors are mainly **the public sector, philanthropists** and **oil and gas companies**. But investors assert that current investments will **not be enough to meet the IPCC target** and that these businesses require **government policy** encouragement to take off.
- Many local, national, and international initiatives about **carbon pricing** have been launched and could represent a solution. However, some **do not contemplate NETs**, and even if included in the trading schemes, carbon prices worldwide are generally **too low** to justify the commercial use of NETs.
- Alternately, manufacturing valuable products by using **carbon as feedstock** could generate a **new market**. This market opportunity is sized at **$6,000 billion** by the New Carbon Economy Consortium, comprised of $4,000 billion for zero/low emission solutions (mainly by making synthetic fuels) and $2,000 billion for negative emission solutions (principally by making building materials and plastics). For example, synthetic fuel made by combining DAC and green hydrogen could provide a business model both competitive and carbon neutral / low carbon. Estimates suggest the production cost could be brought to €1.27 to €1.82 per liter, yet the scalability of the project is still to be proved.
- An alliance of universities, national labs, and nongovernmental organizations (NGOs) created a consortium to encourage the creation of a new carbon economy exploiting this new market. They identify the following:
    - Three primary innovation pathways that hold the greatest potential to activate the new carbon economy: **engineered solutions** (including DAC, CCS, and EW), **biological solutions** (afforestation and reforestation and soil carbon sequestration) and **hybrid solutions** (including BECCS and biochar)
    - Four success drivers for the development of a thriving carbon economy. In their vision, **global hotspots** (areas with rich carbon opportunities) would lead the way. At the same time, strong **supply chains** would be established together with a **data and modeling** repository—all this not forgetting the **workforce development** for tomorrow's needs.
- Government policy should therefore be developed using four principles. In addition to the **support of research, development, and demonstration, short-term opportunities** such as soil carbon sequestration should be taken. However, to allow these technologies to scale, **integrating NETs into emissions accounting and policy support frameworks** is essential, along with making sure current regulations do not prevent future technologies from scaling up by **building system flexibility. These principles, together with defined targets to be included in the 2020 NDC updates, will build the ground needed for the further development of NETs.**

Some orders of magnitude

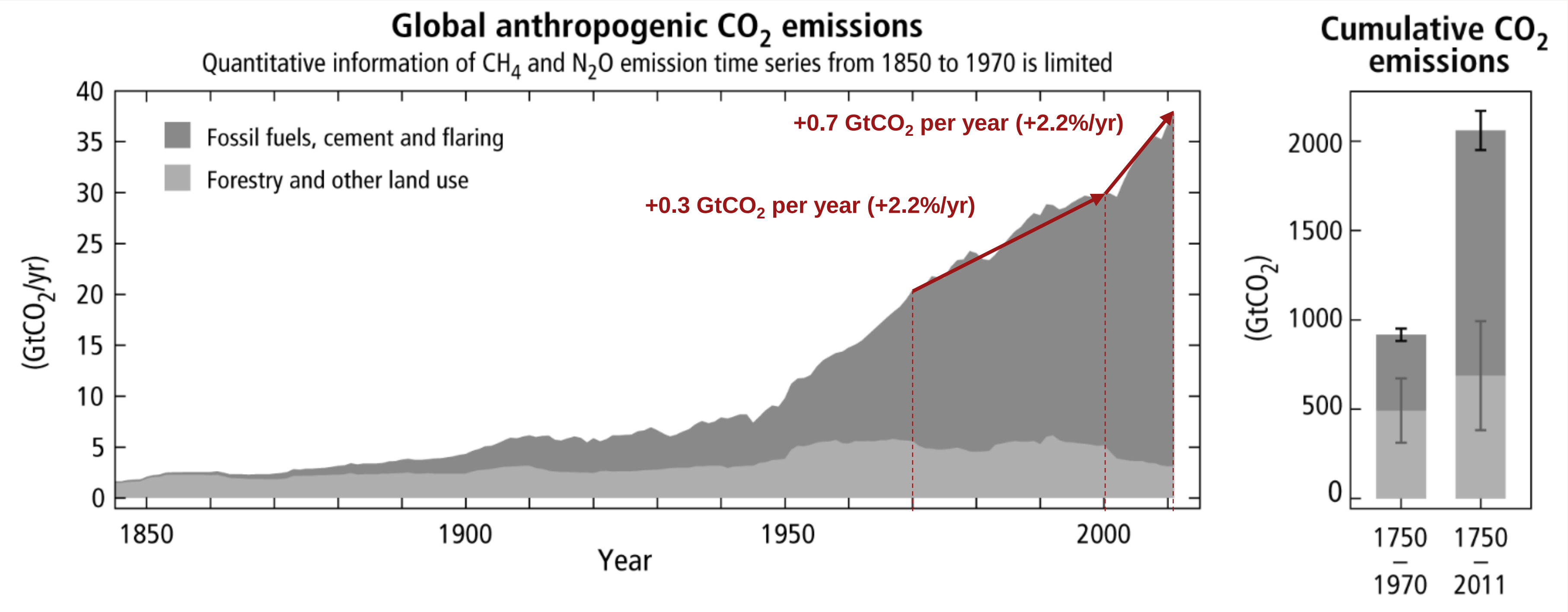
- **Energy-related CO_2 emissions per year**
  - One-passenger car: $5tCO_2$
  - New York City: 50 $MtCO_2$
  - United Kingdom: 500 MtCO2
  - United States: 5 $GtCO_2$
  - World: 40 $GtCO_2$
- **What does 1 Gigaton of CO_2 represent?**
  - 2x the mass of all humans on Earth
  - 1/5 of the mass of all oil consumed each year worldwide
- **What does 1 ton of CO_2 represent?**
  - One return ticket from Paris to New York
  - Worldwide average CO_2 emissions per capita in 2.2 months
- **What is the cost of CO_2 emissions?**
  - Environmental carbon taxes are generally below $20 per tCO_2.
  - Market prices for EOR reached $30 per tCO_2 when the oil price was averaging $100 a barrel.
  - Each ton of CO_2 avoided by using CCS in a coal power plant is likely to cost $53 to $92 per tCO_2.
  - Developed economies generate $2,000 to $6,000 of GDP per ton of CO_2 emitted (carbon-emissions intensity).
- **Largest afforestation and reforestation initiative**
  - African Forest Landscape Restoration Initiative (AFR100)
  - 113 Mha of land, equivalent to the size of Spain and France combined
  - Will capture and store 0.79-1.32 $GtCO_2$ per year
  - Equivalent to about 210 million passenger vehicles taken off the roads
- **Largest BECCS integrated project in operation**
  - Archer Daniels Midland company in Illinois
  - Captures and stores 1 $MtCO_2$ per year
  - Equivalent to about 200,000 passenger vehicles taken off the roads
- **Largest direct air capture integrated project in operation**
  - Climeworks plant in Hinwil, Switzerland
  - Captures and stores 900 tCO_2 a year
  - Equivalent to about 180 passenger vehicles taken off the roads
- **Largest CCS integrated project in operation**
  - ExxonMobil Shute Creek CCS–EOR project in North America
  - Captures and stores 6.5 $MtCO_2$ a year
  - Equivalent to about 1 million passenger vehicles taken off the roads

Table of contents

1. Climate Change and Earth’s Carbon Megacycle

Anthropogenic CO_2 emissions have accelerated during the 20th century

Global anthropogenic CO_2 emissions

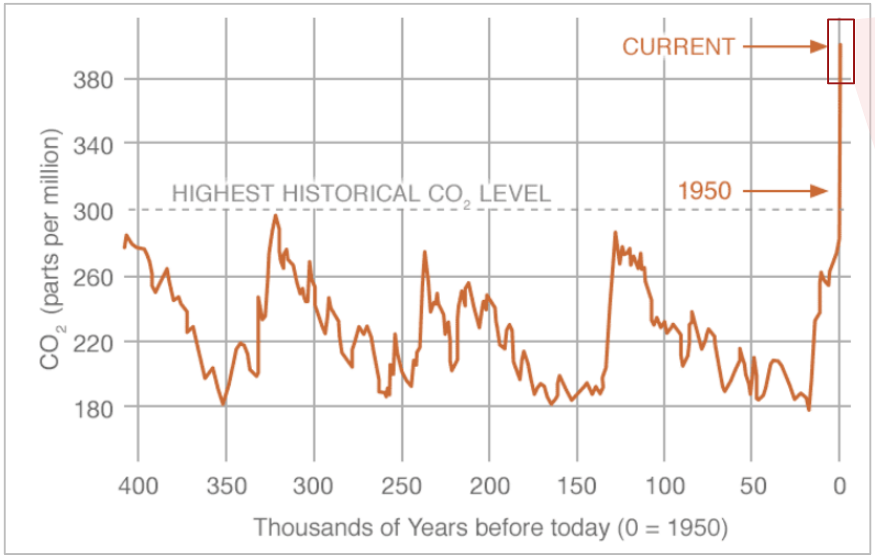


- Since 1970, global CO_2 emissions have been increasing by **0.3 Gt of CO_2 per year** on average, but has accelerated since 2000 **to 0,7 Gt of CO_2** on average per year
- Annual average CO_2 emissions reached **~40Gt per year** compared with about 3Gt per year during the pre-industrial era.
- Other **non-CO_2 GHG** not included in the graph (i.e. CH_4, N_2O and Fluorinated gases), **add another 25% to global warming** (see slide 25)

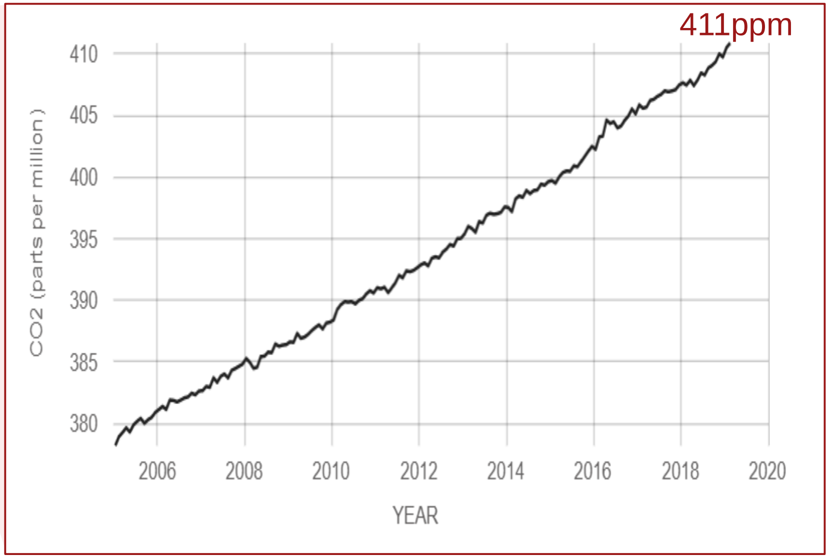
Sources: IPCC "AR5 Synthesis report: Climate change 2014"; Global Carbon Budget 2018; A.T. Kearney Energy Transition Institute analysis

Global CO_2 atmospheric concentration reached 411 ppm in February 2019, by far the highest level over the past 400,000 years

Atmospheric CO_2 concentration over the past 400,000 years



Atmospheric CO_2 concentration over the past 14 years



- The IEA used to refer to its 450 Scenario (e.g. 450ppm of CO_2), as a scenario consistent with having a **50% chance** of limiting the global temperature increase to less than **two degrees** Celsius (°C)

Sources: Global Climate Change: Vital Signs of the Planet, NASA; A .T. Kearney Energy Transition Institute analysis

Most scenarios[1] for global warming are above the 2°C target of the COP21, according to the IPCC

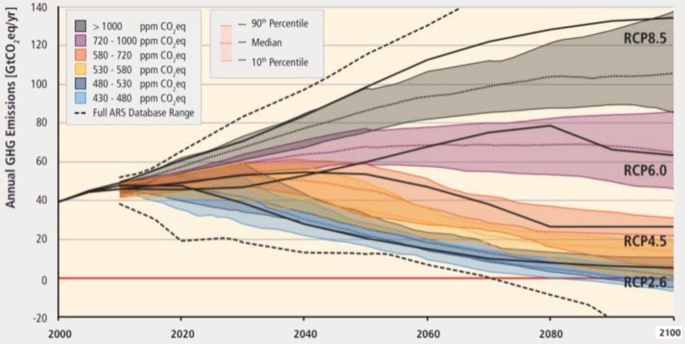
Situation in 2017

- Human activities have caused about **1 °C of global warming** since pre-industrial times (about 1850).
- The Earth's average temperature is **+15°C**.
- Without any naturally occurring GHG's, earth's average temperature would be **-18°C.**

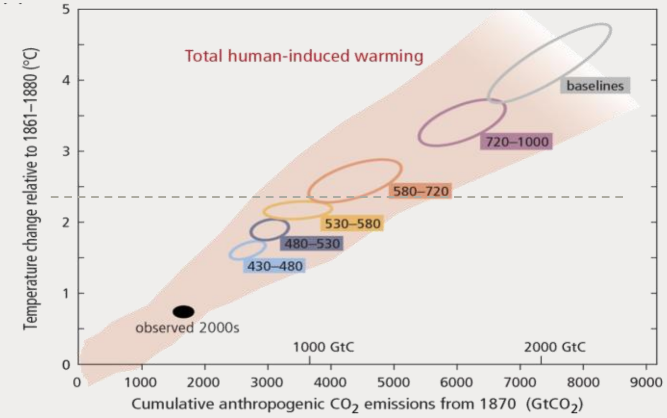
Current scenarios for 2100

- Global warming is likely to reach **+1.5°C between 2030 and 2052** if it continues to increase at the current rate. (high confidence)
- Current **Paris commitments for 2030** would lead to a **warming above 3°C in 2100** relative to 1861 - 1880
- **Business as usual** scenario would lead to a **+4 to +5°C warming in 2100**

GHG emission pathways 2000–2100: all AR5[2] scenarios



Warming versus cumulative CO_2 emissions



1. The IPCC defines scenarios based on the radiative forcing (in W/m2) induced by GHG concentration in the atmosphere. Each scenario is then associated with a likelihood to induce a certain global temperature. For instance, the scenario reaching the atmospheric concentration levels of about 450 ppm CO_2eq by 2100 is consistent with a likely chance of keeping the temperature change below 2°C relative to pre-industrial levels.
2. The Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change

Sources: "Special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways (SR1.5)," Intergovernmental Panel on Climate Change, 2018; A.T. Kearney Energy Transition Institute

Global warming can have a dramatic impact on ecosystems and societies

Key consequences of +1.5°C and +2°C global warming by 2100

"Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present but lower than at 2°C (high confidence). These risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options (high confidence)."

–Intergovernmental Panel on Climate Change

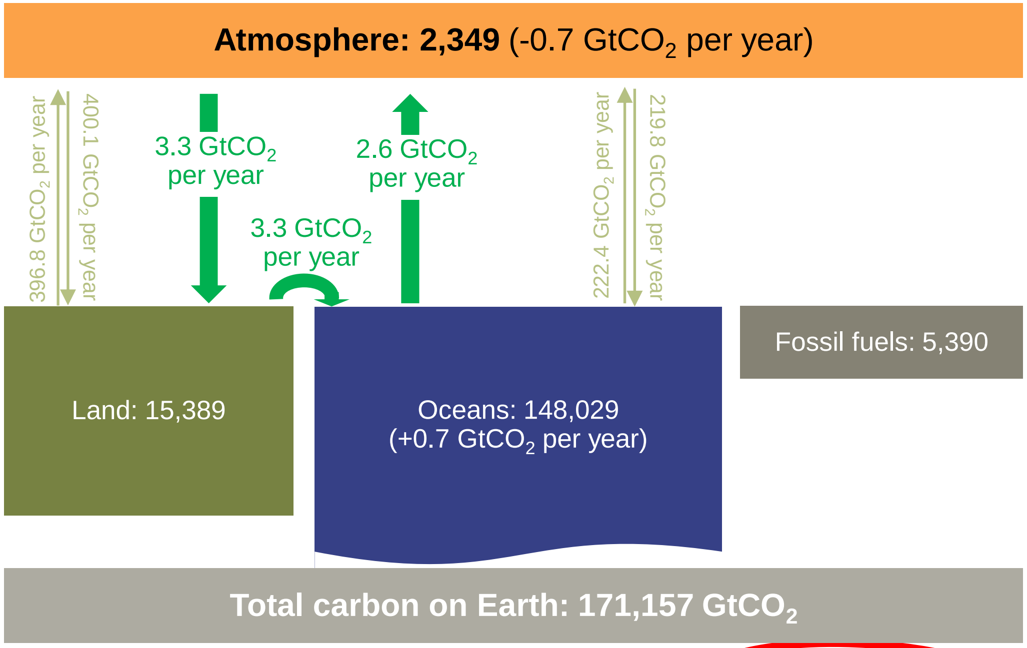
	+1.5°C	**+2.0°C**
Global mean **sea level** rise	0.26 to 0.77 m (medium confidence)	0.36 to 0.87 m (medium confidence)
Biodiversity losses (among 105,000 species studied)	8% of plants 6% of insects 4% of vertebrates (medium confidence)	16% of plants 18% of insects 8% of vertebrates (medium confidence)
Decline of **coral reefs**	70–90% (high confidence)	More than 99% (very high confidence)
Frequency of disappearance of **the Arctic ice cap**	Once per century (high confidence)	Once per decade (high confidence)
Decrease in global annual catch for **marine fisheries**	1.5 million tons (medium confidence)	3 million tons (medium confidence)
Average increase of **heat waves** mean temperature	+3°C (high confidence)	+4°C (high confidence)

Sources: "Special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways (SR1.5)," Intergovernmental Panel on Climate Change, 2018; A.T. Kearney Energy Transition Institute

Before the industrial revolution, natural reservoirs were nearly stable[1], with almost balanced fluxes and constant CO_2 atmospheric concentration

Pre-industrial estimated global distribution of carbon and natural fluxes[2]

(Carbon converted to $GtCO_2$)



Atmosphere: 2,349 (-0.7 $GtCO_2$ per year)

396.8 $GtCO_2$ per year

400.1 $GtCO_2$ per year

3.3 $GtCO_2$ per year

3.3 $GtCO_2$ per year

2.6 $GtCO_2$ per year

222.4 $GtCO_2$ per year

219.8 $GtCO_2$ per year

Land: 15,389

Oceans: 148,029 (+0.7 $GtCO_2$ per year)

Fossil fuels: 5,390

Total carbon on Earth: 171,157 $GtCO_2$

⇅⇅ Gross natural fluxes

↓↷↓ Net natural fluxes

1 $GtCO_2$ = 0.273 GtC

- The **global carbon cycle** can be represented as a series of **carbon reservoirs** in the Earth system, connected to one another by natural **carbon fluxes.**
- **Natural fluxes** have always existed, exchanging large amounts of carbon every year.
- **Atmosphere** is the smallest reservoir, containing only about **1% of the carbon** on Earth. It plays the central role in the global carbon cycle, influencing the carbon concentrations in oceans and on land .
- **Oceans** are by far the largest carbon reservoir on Earth, containing **86% of carbon** on Earth.
- **Land** is the second biggest reservoir, containing about **9% of carbon** on Earth.
- **Fossil fuel** resources and reserves (coal, oil, and natural gas) represent a total amount of carbon of about **5,390 $GtCO_2$** stored in the ground.
- **Fossil fuels**, accumulated from past cycles through sedimentation of organic matter, generally do not contribute to current carbon cycle unless extracted and used.

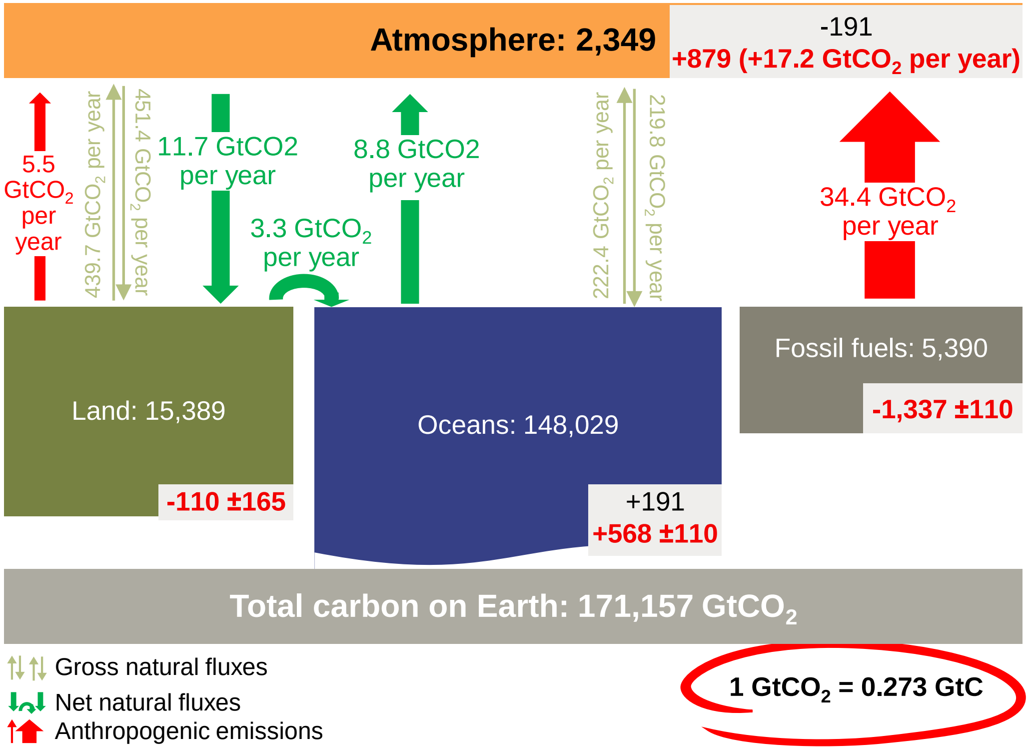
1. The ~50 Wm^{-2} increase in total solar irradiance over the last ~420 million years was almost negated by a long-term decline in atmospheric CO_2, likely due to the silicate weathering-negative feedback and the expansion of land plants, ensuring Earth's long-term habitability.
2. Stocks for the year 1750. Freewater outgassing, volcanism and rock weathering were considered as land-atmosphere fluxes. Individual gross fluxes have typical uncertainties of more than 20% while their differences (net land and net ocean flux) are determined from independent measurements with a much higher accuracy. Average values for were taken. Atmosphere and ocean stocks were calculated as current "would-be" natural stocks minus natural change over the 1750 – 2011 period. Although carbon is not necessarily stored as CO_2, the unit $GtCO_2$ was chosen instead of GtC to allow the direct equivalence with more common emissions values

Source: "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," section 6.1, IPCC; Gavin L. Foster et al. (2017) Nature Communications; A.T. Kearney Energy Transition Institute analysis

Anthropogenic CO_2 emissions have increased the quantity of carbon circulating and caused higher concentration in the atmosphere & oceans

Estimated global distribution of carbon and natural and anthropogenic fluxes

(Carbon converted to $GtCO_2$)



- Since the beginning of the industrial era, **fossil-fuel extraction** has resulted in the transfer of a significant amount of carbon (about **1,337 $GtCO_2$**) from fossil fuels to the atmosphere, altering carbon budgets and fluxes.
- About **40 Gt of CO_2** per year human emissions correspond to 5.5 from land and 34.4 from fossil fuels
- But not all emissions stay in the atmosphere:
  - **Land** has a net absorption of **~30%**[1] of yearly. anthropogenic carbon emissions.
  - **Oceans** also capture atmospheric carbon, and represent **43%**[2] **of the net natural CO_2 removal.**
- The amount of carbon in the **atmosphere** has risen **29%** since 1750, and it is increasing faster than ever.
- In addition to climate change, higher CO_2 concentration in the atmosphere is causing fundamental changes in the natural mechanisms within each reservoir.

1. ~30%=11.7/(34.4+5.5). (2) 43%=8.8/(8.8+11.7)

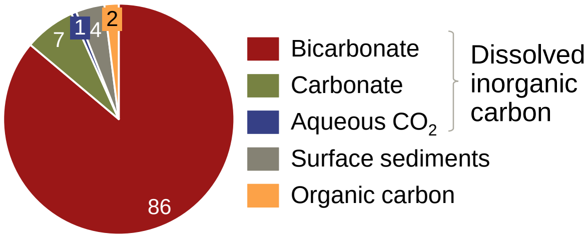
Notes: Carbon stocks are for 201 Uncertainties for net fluxes are as follows: fossil fuels – atmosphere ±8, land – atmosphere ±2.6, atmosphere – oceans ±8, atmosphere – land ±2.6. Fluxes are for the decade 2008–2017. Red numbers denote cumulative changes due to anthropogenic carbon over the industrial period 1750–201 Black numbers in grey boxes in the reservoirs denote cumulative changes of natural carbon over the same period. These numbers may have big uncertainties, yet they show the magnitude of anthropogenic activities; 19.4 – 17.2 = 2.2 $GtCO_2$ per year is the budget imbalance between modeled atmospheric uptake and observations.

Sources: Global Carbon Budget 2018; "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," section 6.1, IPCC; A.T. Kearney Energy Transition Institute analysis

In the oceans, dissolved carbon is unevenly distributed and varies with oceanic T°

Characteristics of the carbon-oceanic reservoir

Mass % of carbon in the oceans



Oceanic carbon is stored in various chemical forms

- **Aqueous CO_2** reacts with water to form carbonic acid, which dissociates into **bicarbonate** (**~86%**) and **carbonate** (**~7%**) ions:

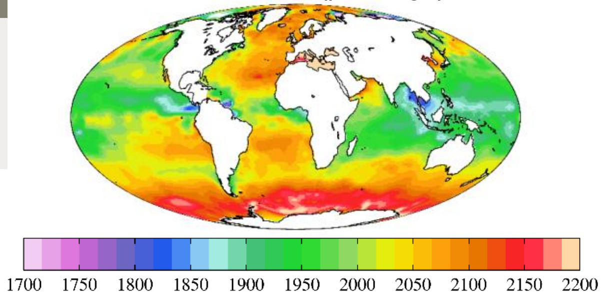
$$CO_2(aq) + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^{2-} + 2H^+$$

- This dissociation increases H^+ ion concentration, leading to **ocean acidification**[1]
- **Surface sediments** (**~4%**) on the sea floor are the most stable oceanic sub-reservoir.
- Most of the **organic carbon** (**~2%**) is in dead form. **Marine biota** (living organisms) only incorporate the equivalent of 11 $GtCO_2$, representing **less than 0.01%** of carbon in the oceans.

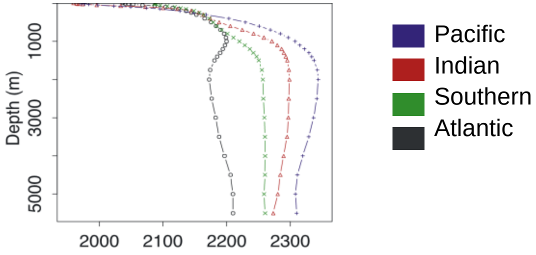
Carbon concentration in surface oceans varies with T°

- **CO_2** enters the ocean by **dissolution** due to the partial pressure differential between the surface water and the lower atmosphere and to CO_2 **solubility** in seawater.
- Because CO_2 solubility is higher in cold waters, the **Southern Ocean** can have up to **25% higher surface concentrations** than tropical waters.

Surface dissolved inorganic carbon concentration (μmol kg^{-1})



Average profile of dissolved inorganic carbon concentration segregated by ocean (μmol kg^{-1})



Carbon concentration increases with oceans water depth

- Due to cold waters underneath the surface, carbon concentrations **increase 5 to 15%** up to **1000 m**, after which remain approximately constant.
- Below **3000 m**, CO_2 is **denser** than water and falls to the **ocean floor**, forming a theoretically **stable reservoir**

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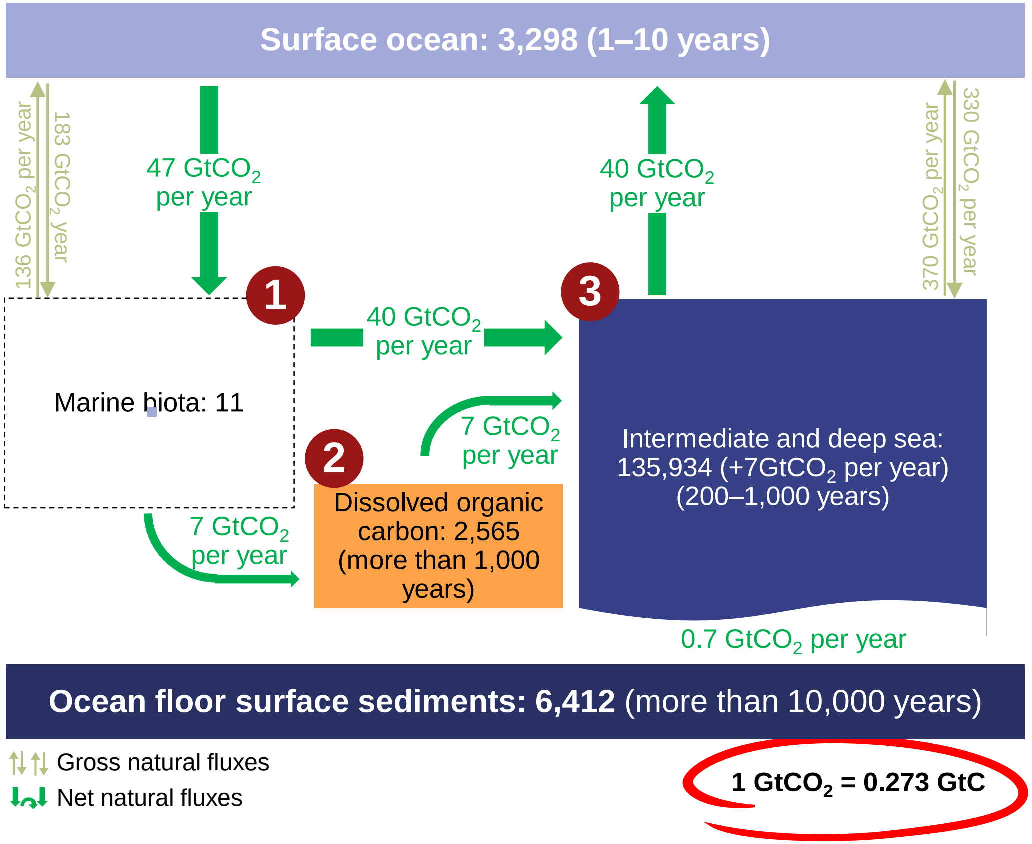
1. Ocean acidification is analyzed in more detail in slide 82

Sources: Global Carbon Budget 2018; SCRIPPS Institution of Oceanography; the Global Ocean Data Analysis Project; "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," section 6.1, IPCC; MIT; A.T. Kearney Energy Transition Institute analysis

The oceanic carbon uptake is controlled by the net amount of carbon entering the intermediate and deep sea

Oceanic carbon cycle and sub-reservoirs[1]

(Carbon converted to $GtCO_2$)



① Despite its small size, **marine biota** plays a fundamental role in the oceanic carbon uptake. Its fluxes are due to the biological, carbonate, and microbial pumps. **47 $GtCO_2$ per year** are the net result from photosynthesis (↓) and respiration, decomposition and shell remineralization (↑). **40 $GtCO_2$ per year** are transported to the intermediate and deep sea, and **7 $GtCO_2$ per year** are transformed in dissolved inorganic carbon, keeping the sub-reservoir in a **steady state.**

② **Dissolved organic carbon** plays the central role in the microbial pump. **7 $GtCO_2$ per year** are added to this reservoir and remain for more than **1,000 years**. Removal is done at the same rate of **7 $GtCO_2$ per year**, keeping this sub-reservoir at a **steady state.**

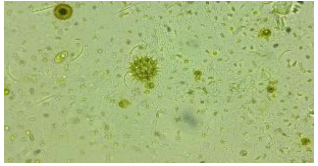
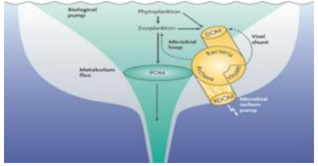
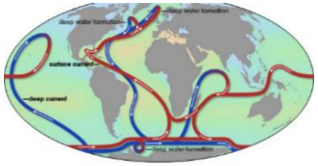
③ Although the **intermediate and deep sea** receives carbon from the two previous sub-reservoirs, it releases **40 $GtCO_2$ per year** to the surface ocean through the solubility pump. Nevertheless, the total uptake is positive (**+7 $GtCO_2$ per year**), and the carbon stored there can remain for **200 to 1,000 years**.

1. Although carbon is not necessarily stored as CO_2, the unit $GtCO_2$ was chosen instead of GtC to allow the direct equivalence with more common emissions values
2. Numbers in parenthesis inside boxes refer to the carbon residence time in each sub-reservoir.

Sources: Plymouth Marine Laboratory; University of California; Alex Thomas, University of Edinburgh School of GeoSciences; Ocean and Climate platform; Jiao, N., et al. (2010); “Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,” section 6.1, IPCC; Shen, Y. & Benner, R. (2018); Riebesell, U. et al (2009); A.T. Kearney Energy Transition Institute analysis

Climate change modifications should diminish the ocean's ability to store carbon

Ocean reservoir pump mechanisms

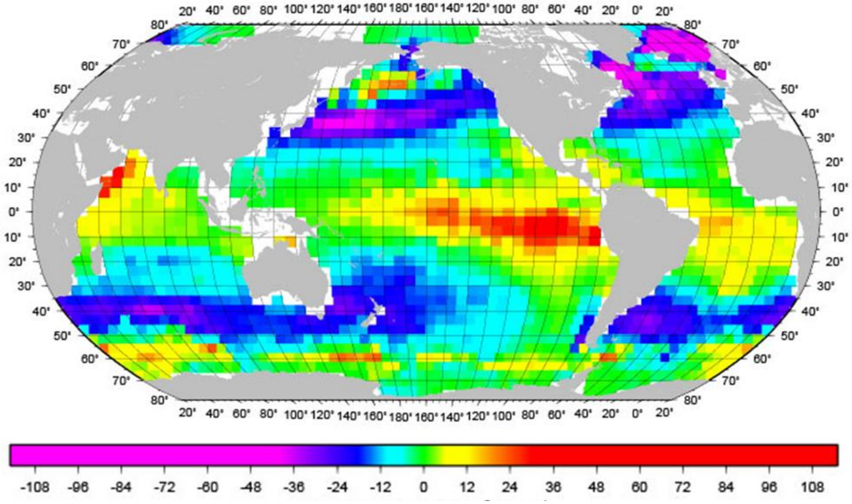
Mechanism name	**Description**	
Biological pump 	• **Phytoplankton and algae** convert dissolved inorganic carbon through photosynthesis into **organic matter** that is incorporated into marine biota. • This process is limited by the availability of **light** and **nutrients** such as **iron** in the water.	• Because of the reduced supply of iron dust from winds and other nutrients from weaker tropical upwelling, **climate change** can lead to a **weaker biological pump**, reducing oceanic uptake and further **worsening climate change**.
Carbonate pump 	• **Calcareous plankton** in the surface ocean produces calcium carbonate **$CaCO_3$ (shells).** • **CO_2** is released in the $CaCO_3$ formation, increasing CO_2 concentration in surface waters **(negative effect).**	• Shell corrosion from **ocean acidification** can **weaken the carbonate pump**. The type of feedback this poses to climate change is still nonconsensual.
Microbial pump 	• **Refractory dissolved organic carbon** (RDOC) is the remaining product of **bacteria decomposition**. Most of the organic carbon is under the form of RDOC. • Removal is done by **abiotic processes** such as photo degradation.	• Assuming a **constant rate of production**, the sub-reservoir size of RDOC could increase as the thermohaline circulation slows, providing a long-term **global warming reduction** as a result of higher residence time in this reservoir than in the intermediate and deep sea.
Solubility pump 	• Carbon-rich **cold waters** close to the poles **descend** as part of the **thermohaline circulation (330 $GtCO_2$ per year).** • **Upwelling** in warm **tropical regions** brings **370 $GtCO_2$ per year** back to surface waters	• Global warming is **raising the sea-surface temperature**, leading to a **lower CO_2 solubility** and reduced thermohaline circulation (due to ocean stratification). Both effects are expected to **decrease** the oceanic carbon uptake by **3 to 20%** until 2100.

Sources: Plymouth Marine Laboratory; University of California; Alex Thomas, University of Edinburgh School of GeoSciences; Ocean and Climate platform; Jiao, N., et al. (2010); "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," section 6.1, IPCC; Shen, Y. & Benner, R. (2018); Riebesell, U. et al (2009); A.T. Kearney Energy Transition Institute analysis

Oceans are carbon sinks, but mechanisms are very complex and poorly understood

Mean modeled atmosphere - ocean net flux for the year 2000

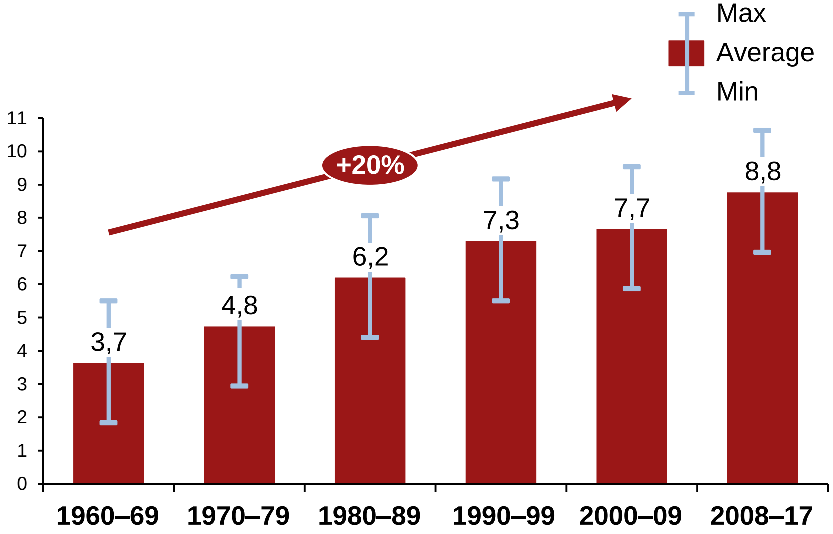
(gC m^{-2} per year)



- Ocean flux with the atmosphere is estimated based on **ocean models**, which are in turn based on measured data.
- Buoys in the ocean measure the CO_2 **concentration differential** between the water and the atmosphere, producing **data** that allows us to create the graph above.
- **Cold waters** combined with **high atmospheric concentrations** make the regions with the **highest oceanic uptake**. Tropical upwelling regions emit as part of the thermohaline circulation.

Global atmosphere - ocean flux by decade

($GtCO_2$ per year)



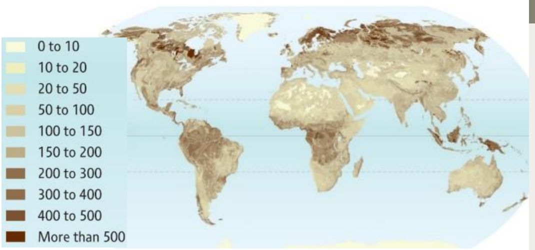
- Oceanic uptake increased **20% per decade** during the 1960–2009 period.
- **Lack of data** is one of the biggest problems when assessing oceanic uptake. In addition, different models give different results, illustrating the **high uncertainties regarding** their assessment.
- Because several of the underlying processes are interlinked and nonlinear, the sign and magnitude of the ocean's carbon cycle **feedback to further climate change** remains poorly quantified.

Sources: Deep-Sea Research II; Global Carbon Budget 2018; A.T. Kearney Energy Transition Institute analysis

Land carbon concentration is higher in tropical and boreal regions

Characterization of the land-carbon reservoir

Land carbon concentration (ton ha^{-1})

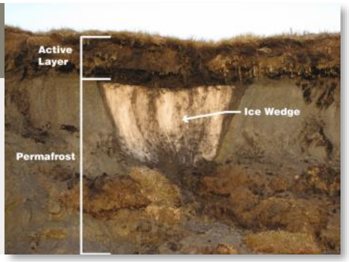


Global surface concentration strongly varies with the latitude

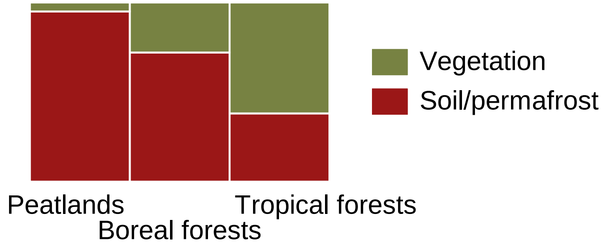
- Carbon is absorbed through **photosynthesis** during the day and released back to the atmosphere through **respiration**, **fires,** or **decomposition**.
- **Organic carbon** accumulates as **vegetation** or as dead biomass in **soils** and **permafrost.**
- Soils hold **46%** of the carbon on land, followed by permafrost (**40%**) and vegetation (**14%**).
- Although smaller in area, **boreal biomes** store almost twice as much carbon as **tropical forests**.

Boreal biomes store most of their carbon in soils and permafrost

- In **peatlands**, a small layer of vegetation covers a much larger carbon reservoir: **More than 95%** of the carbon stored is in the form of dead frozen plant material in the **permafrost.** Anaerobic conditions along with low temperatures prevent this dead carbon from decomposing.
- **Boreal forests** hold **72%** of their carbon in **soils**, with the remaining in vegetation.



Estimated carbon mass distribution segregated by biome



Tropical forests store carbon in vegetation

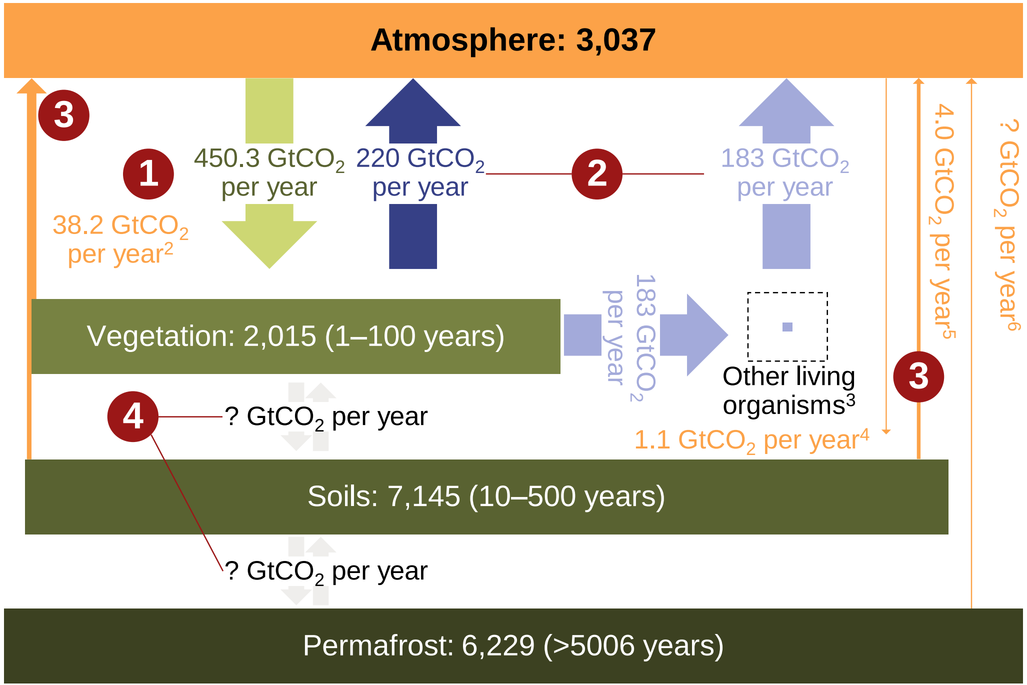
- With **62%** of the carbon into **vegetation**, **tropical forests** exchange massive amounts of carbon (about **150 $GtCO_2$ per year**) with the atmosphere through photosynthesis and respiration.
- However, carbon doesn't stay here for long. Fast decomposition after plants die means that the average age of carbon in these soils is **10 times lower** than in boreal soils.

Sources: Kasischke E.S. (2000); Nigel Roulet, McGill Faculty of Science; Trumbore S. (2000); Blais, AM., et al (2005); A.T. Kearney Energy Transition Institute analysis

The land carbon uptake is controlled by the net amount of carbon entering vegetation and soils

Land carbon cycle and sub-reservoirs[1]

(Carbon converted to $GtCO_2$)



⇅⇅ Disturbance, rock weathering, volcanism, and freshwater outgassing and thawing permafrost (from left to right)

↓ Photosynthesis ↑ Plant respiration ↑ Others' respiration

1 $GtCO_2$ = 0.273 GtC

① **Plants** convert atmospheric CO_2 though **photosynthesis** (about **450.3 $GtCO_2$ per year**) into organic matter in vegetation, where it stays for 1 to 100 years.

② **Plant respiration** during the night is responsible for releasing **about 220 $GtCO_2$ per year** back to the atmosphere. **About 183 $GtCO_2$ per year** of the remaining carbon are incorporated in the food chain and **respired** back into the atmosphere at the same rate. The **47.3 $GtCO_2$ year** remaining in vegetation are called the net ecosystem productivity (NEP).

③ The final **land uptake** (**6.2 $GtCO_2$ per year**) is the NEP summed with the uptake due to **rock weathering**[4] and then discounting the costs of **disturbance** (fires, diseases, and land-use change), **volcanism and freshwater outgassing**[5], and **thawing permafrost**[6]. Human **land-use change** emissions (**5.5 $GtCO_2$ per year**) refer to the human related fraction of total disturbance.

④ The fluxes **soils-permafrost** and **soils-vegetation** are not yet globally quantified but are of great importance because of the long residence time in the soils and permafrost sub-reservoirs (**10 to more than 500 years**).

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1. Although carbon is not necessarily stored as CO_2, the unit $GtCO_2$ was chosen instead of GtC to allow the direct equivalence with more common emissions values ; 2. Calculated as the remainder for 454 $GtCO_2$ per year gross land uptake and 6.2 $GtCO_2$ per year net land uptake assuming negligible thawing permafrost emissions. ; 3. Stock for other living organisms was not found in the literature. ; 4. Weathering is the natural process of rock decomposition via chemical and physical processes where CO_2 is spontaneously consumed and converted to bicarbonates (and/or carbonates): $CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$ These compounds are dissolved in rainwater and eventually end up in the ocean. ;
5. Volcanism and freshwater outgassing are natural fluxes that are assumed to have remained constant since the pre-industrial era.
6. Definition in the following slide. Exact value for current thawing permafrost emissions was not found in the literature and so was assumed negligible.

Sources: Global Carbon Budget 2018; US Department of Energy (2008), section 3; IPCC (2013), "AR5-WGI, section 6.1"; IPCC Special report on the impacts of global warming of 5°C (2018) Chapter 4; A.T. Kearney Energy Transition Institute analysis

Climate change feedback loops should diminish the land’s ability to store carbon

Land reservoir’s main feedback loops

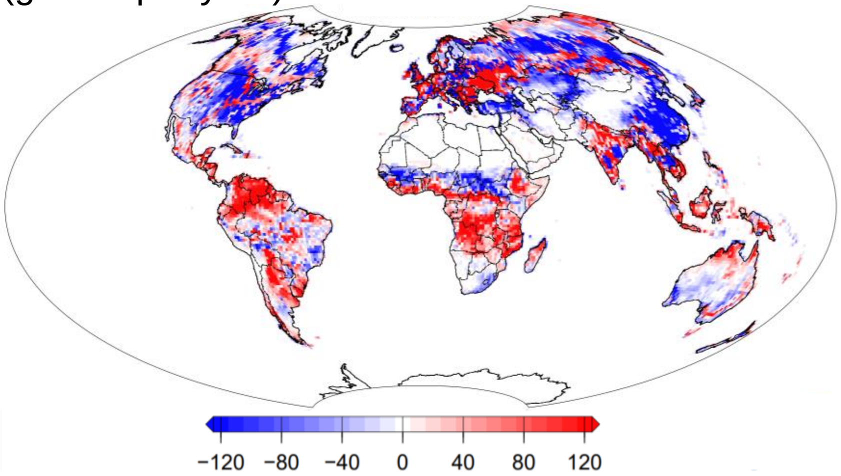
Feedback name	Description	
Thawing permafrost 	• **Permafrost melt** due to **rising temperatures** creates huge craters, such as one in Siberia that is 1 km wide and 86 meters deep. These craters expose the dead organic carbon to bacteria that **decompose** it, **releasing CO_2 and methane** to the atmosphere, further enhancing global warming.	• It is estimated that this mechanism can contribute with **0.33 to 0.70 GtCO_2 per year** additional emissions at 2°C of global warming, which does not indicate a tipping point.
Desertification 	• **Vegetation cover loss** causes an increase in soil erosion and reduced evapotranspiration, which reduces soil fertility and precipitation, further enhancing desertification.	• **Land-use change** already accounts for emissions of **5.5 GtCO_2 per year.**
CO_2 fertilizing effect 	• It has been proven that **higher atmospheric CO_2** concentrations in the atmosphere have a **fertilizing effect** in plants, leading to a **higher uptake** and so reduction of atmospheric CO_2 concentration.	• It is difficult to predict the increased carbon uptake due to this mechanism.
Ozone and aerosols  	• **Higher** tropospheric **ozone concentration** and **lower aerosols concentration** are among the climate change consequences. Both lead to **lower photosynthesis efficiency** and **reduced vegetation carbon uptake**, further enhancing climate change.	• Although it is difficult to predict the impact of this mechanism, it is expected that the combination with the CO_2 fertilizing effect will result in a **worse climate change**.

Sources: Higginbottom (2014), Yumashev, D. (2019); Cox, P., et al. (2015); A.T. Kearney Energy Transition Institute analysis

Some models show that land CO_2 capture has been constantly increasing, but high uncertainties dictate this flux

Mean modeled atmosphere - land net flux for the year 2016[1]

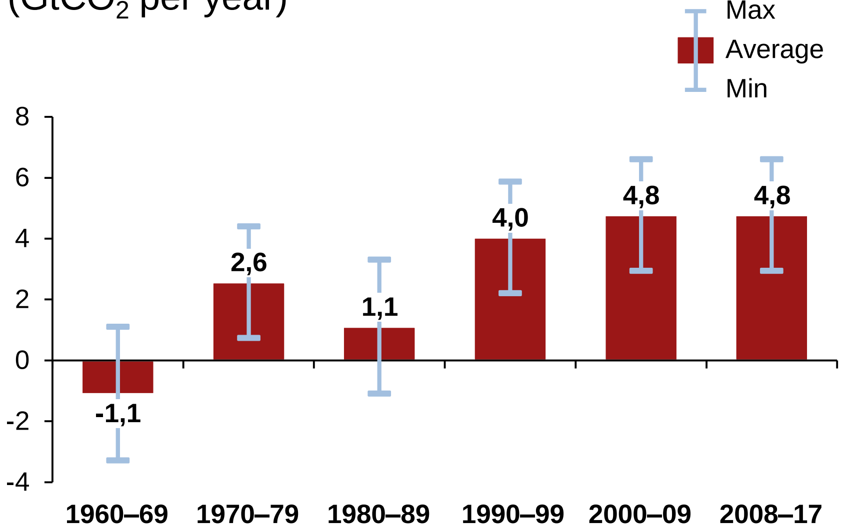
(gC m^{-2} per year)



- Atmosphere-land net flux has a big **geographic variability**:
  - **Positive fluxes** (red colors) indicate regions in which the land biosphere is a net source of CO_2 to the atmosphere (due to deforestation, fires, and other phenomena), while
  - **Negative fluxes** (blue color) represent CO_2 uptake by the land biosphere, but the possible saturation of the blue areas could reduce its capacity to capture CO_2.
- The **uncertainty** of the values displayed above is quite high, ranging from 100 to 400 gC m^{-2} per year in most regions.

Global atmosphere – land flux by decade

($GtCO_2$ per year)



- Globally, net land uptake (including land-use change emissions) is positive, and estimated to have **increased** between 1960 and 2009.
- Estimations for the atmosphere – land net flux are based on the average of the results of several **dynamic global vegetation models**[2] (DGVMs), which produce maps like the one on the left
- **Results vary significantly** across the several DVGMs. While some overestimate carbon fluxes, others even say the flux is negative, suggesting that the land sink is actually a source, leading to **high uncertainties** carried on to the global flux estimate.

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1. This map represents land-to-atmosphere carbon exchange from photosynthesis and respiration in terrestrial ecosystems, and a contribution from fires. It does not include fossil fuel emissions. From NOAA Earth System Research Laboratory CarbonTracker CT2017 release
2. Estimates for land-use change emissions from DVGMs vary slightly from the same values obtained by bookkeeping methods, which is why the 2008-2017 yearly flux in this slide is 4.8 $GtCO_2$ per year instead of the 6.2 (=17-5.5) $GtCO_2$ per year depicted in slide 14

Sources: Global Carbon Budget 2018; A.T. Kearney Energy Transition Institute analysis

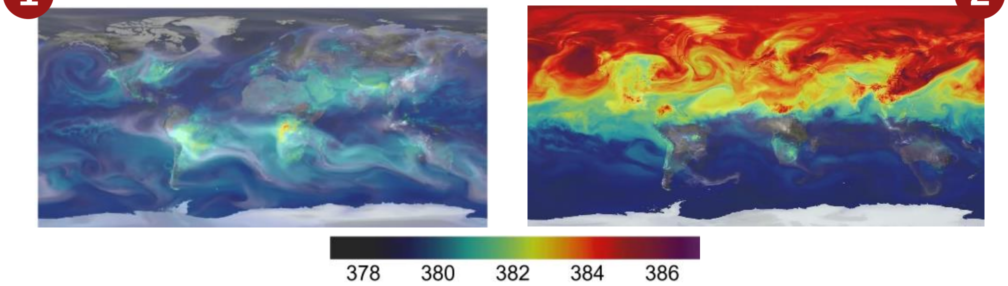
CO_2 atmospheric concentration globally increasing, but subject to seasonal fluctuations and is site dependent

Seasonal variation of CO_2 atmospheric concentration

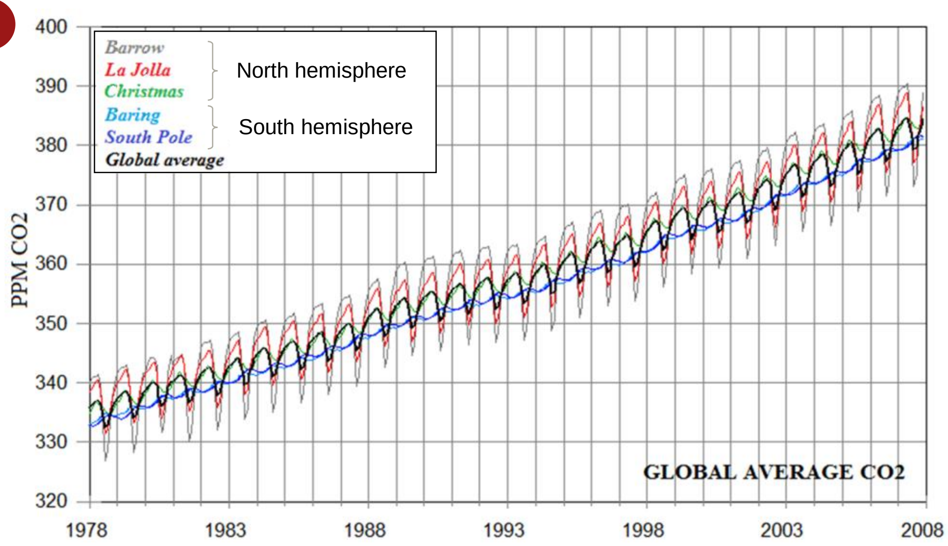
(ppm)

① **September** (10/13/06 03:00 GMT)

May (05/08/06 05:00 GMT) ②



③



① Atmospheric **concentrations** are the **lowest** and most **evenly distributed** across the globe around **September**, after forests in the northern hemisphere have absorbed CO_2 during summer. The higher concentration in the **Congo Rainforest** is because of **plant respiration** during the **night**. Approximately the same amount of carbon will be absorbed during the day. This daily cycle only impacts **local concentrations** and is kept approximately constant throughout the year.

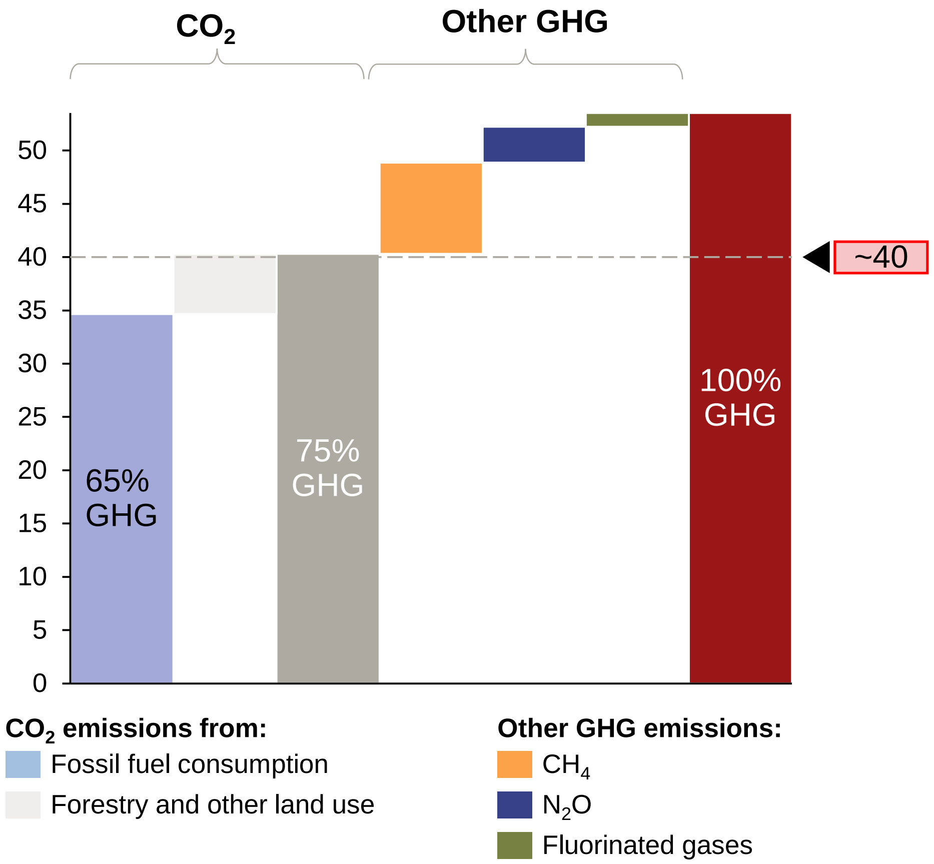
② Global average CO_2 concentration reaches its **peak** in **May**, with **accumulated emissions** over the **winter** in the **north hemisphere** not being taken by plants. Although plants in the South hemisphere absorb carbon during **summer**, **mixing** between the two hemispheres is **too slow** for them to be absorbing the same carbon emitted in the North hemisphere.

③ Seasonal variation **amplitude** can be up to **18 ppm** in the Barrow station in Alaska. The **phase is shifted** in the south, but the amplitude there is only 1-3 ppm.
The ocean plays a smaller role in this yearly cycle. This is because carbon exchanges with the ocean are slower and have a smaller seasonality effect.

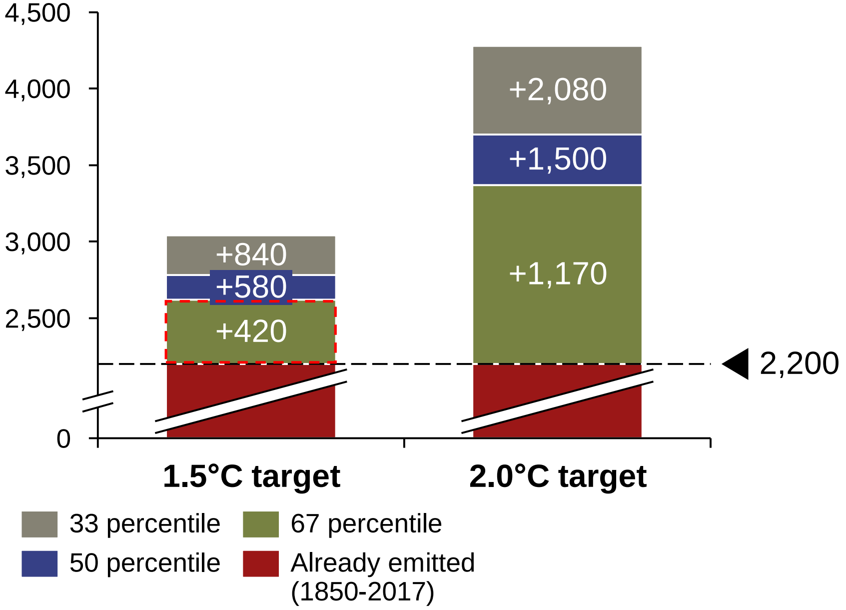
Sources: climate.nasa.gov; Monroe, R. (2013); A.T. Kearney Energy Transition Institute analysis

In 2017, global CO_2 emissions amounted to ~40Gt, about the tenth of the remaining carbon budget related to the +1.5°C target

Global GHG emissions in 2017 ($GtCO_2eq$)



Remaining carbon budget for the +1.5°C and +2.0°C targets ($GtCO_2$)

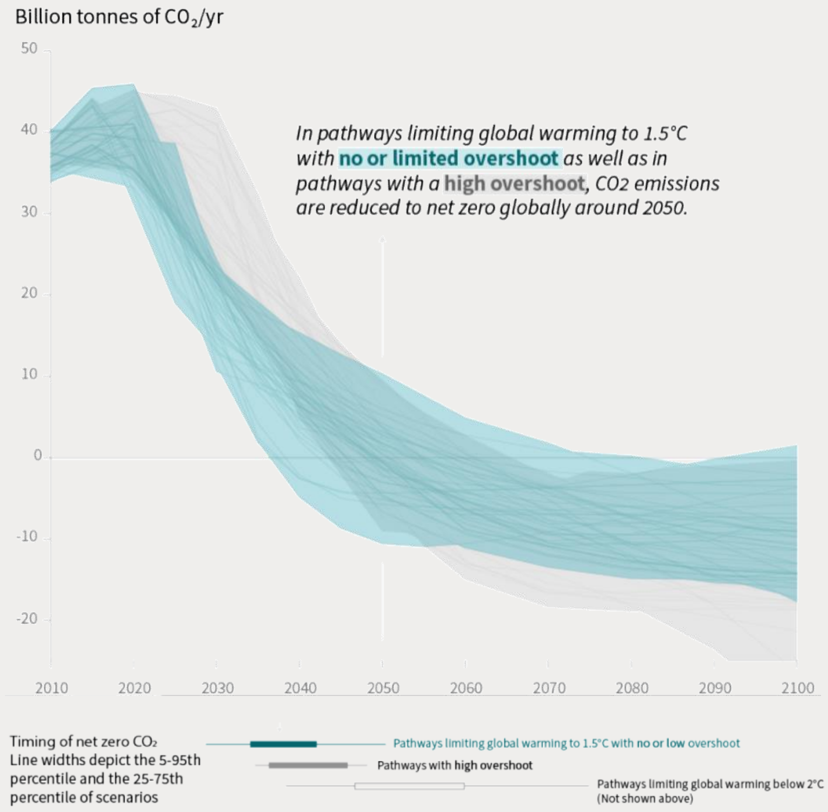


- There are several estimates and various uncertainties related to past CO_2 emissions and remaining carbon budgets with regards to global warming scenarios.
- Nevertheless, the IPCC revisited its analysis in 2018 and came up with the following results: keeping global warming below 1.5°C and 2.0°C would respectively require to stick to the carbon budget of 420 Gt CO_2 and 1,170 Gt CO_2 (67 percentile).

Sources: Global Carbon Budget 2018; IPCC (2018) "SR5 – Chapter 2"; BP (2015) "Statistical review"; United Nations Environment Programme, Emissions Gap Report 2018; A.T. Kearney Energy Transition Institute analysis

Limiting warming to 1.5°C would require an unprecedented level of change

Global total net CO2 emissions



Required changes

CO_2 emissions targets

- Reduce CO_2 emissions by about **45% by 2030** (from 2010 levels).
- Reach **net zero CO_2 emissions around 2050.**

Transformation of energy uses and systems

- Make deep emission cuts in all sectors, including transport and buildings:
  - Oil and especially gas persist longer; gas use rises by 2050 in some pathways.
  - Coal declines steeply; zero in electricity by 2050.
  - Increase investment in low carbon options, with **renewables supply 70 to 85% of electricity in 2050** (scale up in annual investment in low carbon energy and energy efficiency by factor of five by 2050).

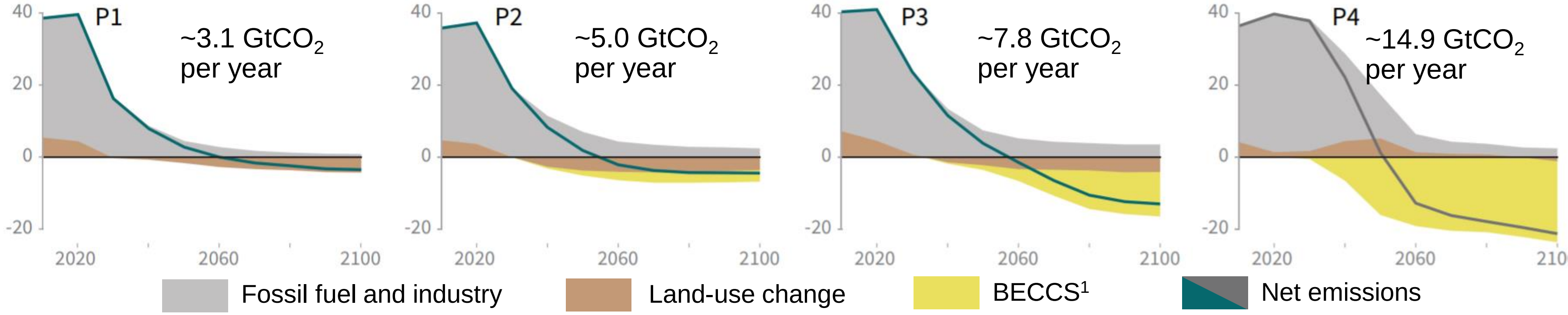
Changes in land use and urban planning

Sources: IPCC (2018) "SR1.5 – Summary for Policymakers" (2018); A.T. Kearney Energy Transition Institute analysis

Climate change mitigation scenarios require deploying negative emission technologies in proportion to CO_2 emission levels

Possible CO_2 emission pathways

($GtCO_2$ per year)



- **Negative emission technologies** are integrated into all possible CO_2 emission pathways.
- **P1** and **P2** require, among other measures, **a decrease of final energy demand** of 15% and 5% in 2030 relative to 2010, thus limiting the need of negative emission technologies to an average of ~3.1 and ~5.0 $GtCO_2$ per year (from 2020 to 2100) respectively.
- **P3** also relies on a **high share of renewables** in the electricity mix (48%) and **big reductions in coal** (-75% compared to 2010) in 2030. However, **oil** consumption is only **reduced 3%** and **gas even increases 33%**. With a **final energy demand increase** of 17%, an average of **~7.8 $GtCO_2$ per year** should be captured by negative emission technologies from 2020 to 2100.
- The **resource and energy intensive scenario P4** predicts an **overshoot** of the 1.5°C target, followed by massive implementation of non-land negative emission technologies (average **~14.9 $GtCO_2$ per year** from 2020 to 2100).

Depending on future energy efficiency and mix, negative emission technologies should represent between 3.1 and 14.9 $GtCO_2$ per year.

---

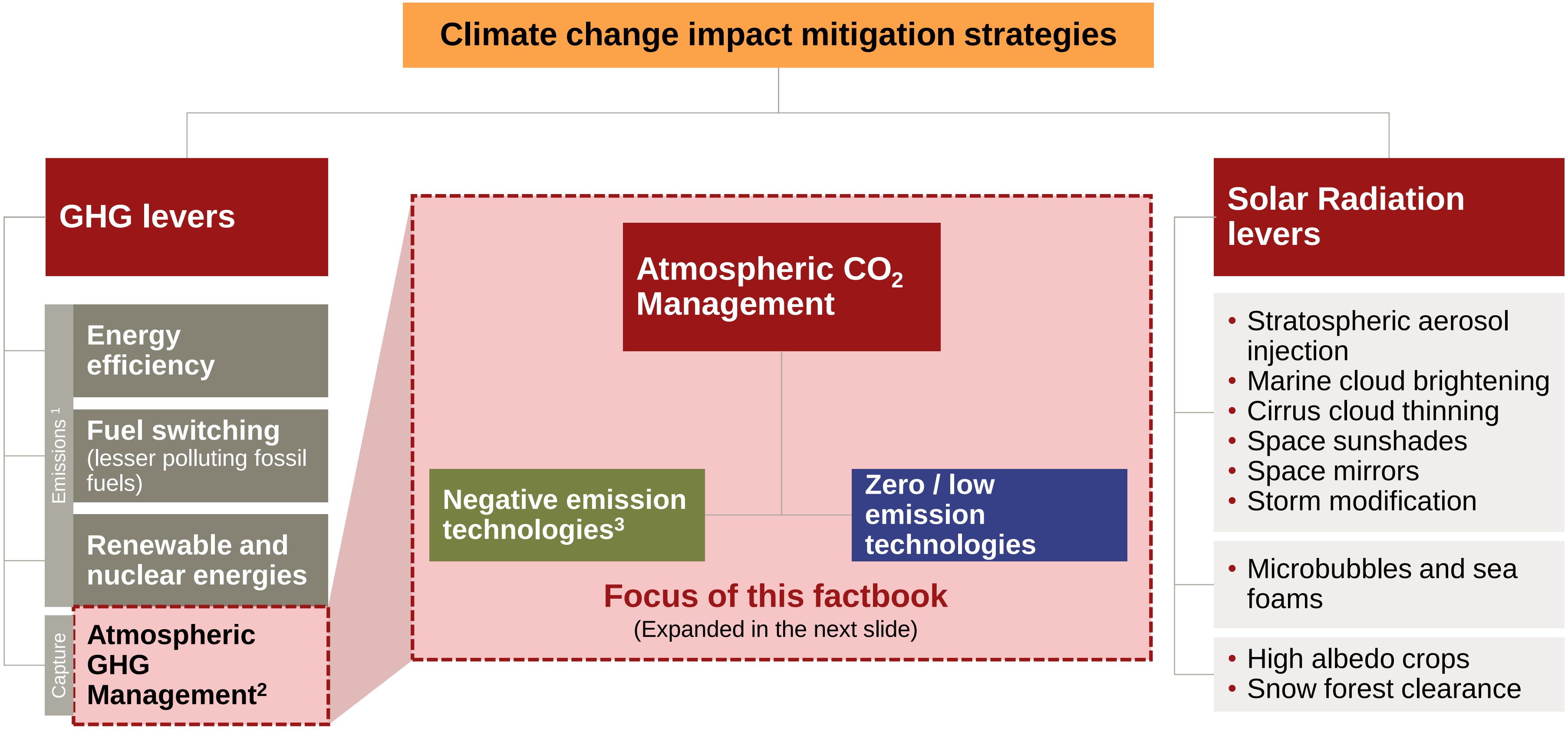
1. BECCS: Bioenergy with CCS. As showed further in the FactBook, other technologies can be used instead. The energy deficit that would be left by the replacement was assumed to be covered by renewables, thus not increasing the necessary carbon capture values

Sources: IPCC (2018) "SR5 – Summary for Policymakers" and "Chapter 2"; A.T. Kearney Energy Transition Institute analysis

2. Negative Emission Solutions

Multiple strategic options have been debated to alleviate the impact of climate change

Not exhaustive



Climate change impact mitigation strategies

GHG levers

Emissions [1]

- **Energy efficiency**
- **Fuel switching** (lesser polluting fossil fuels)
- **Renewable and nuclear energies**

Capture

- **Atmospheric GHG Management**[2]

Atmospheric CO_2 Management

- **Negative emission technologies**[3]
- **Zero / low emission technologies**

Focus of this factbook

(Expanded in the next slide)

Solar Radiation levers

- Stratospheric aerosol injection
- Marine cloud brightening
- Cirrus cloud thinning
- Space sunshades
- Space mirrors
- Storm modification

- Microbubbles and sea foams

- High albedo crops
- Snow forest clearance

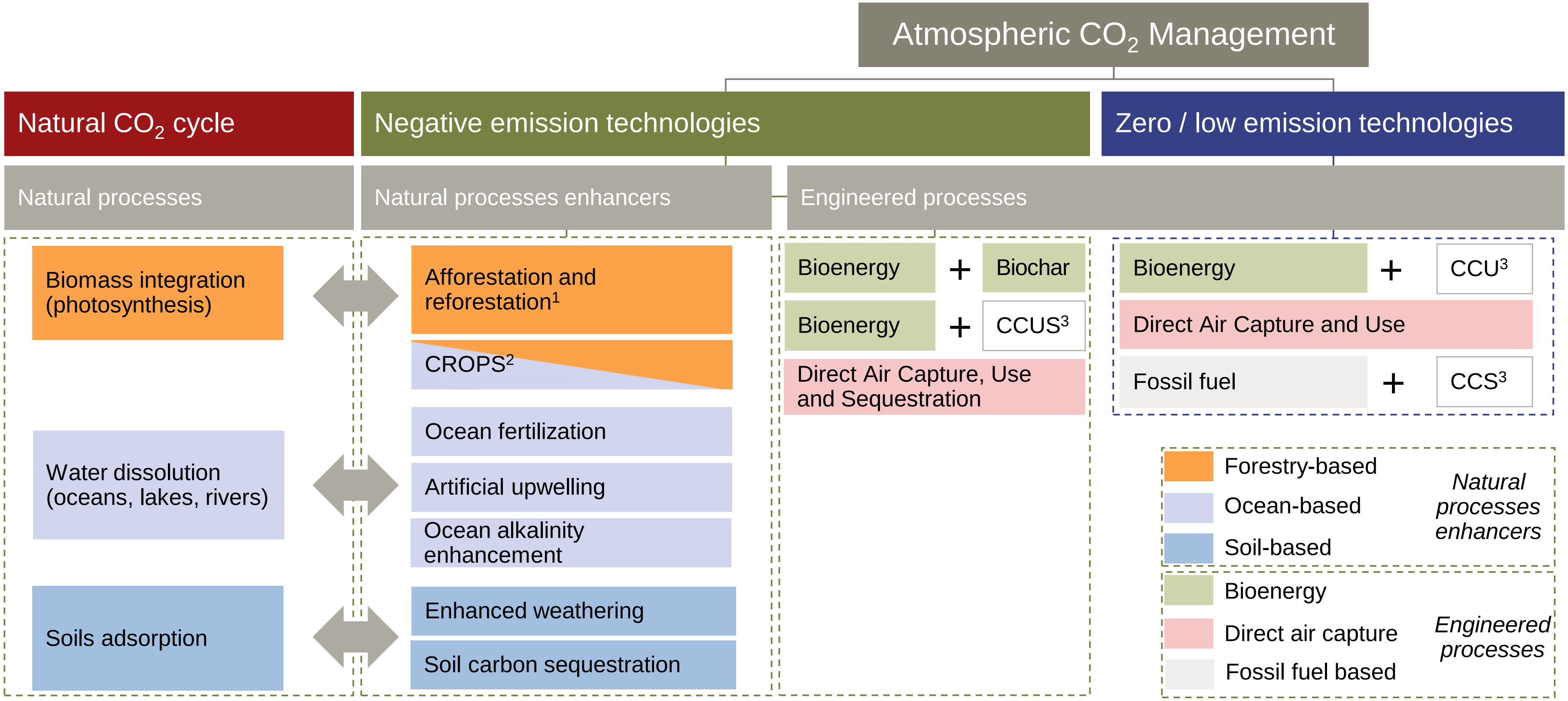
Note: (1) Other options concerning agriculture, transport, and other economic sectors are not included; (2) management of non-CO_2 GHG (i.e. CH4, N_2O and Fluorinated gases) are not included in the study – the study therefore focuses CO_2 only; (3) Negative Emission Solutions are also called Carbon Dioxide Removal

Source: A.T. Kearney Energy Transition Institute analysis

Carbon dioxide removal technologies can be further classified as either negative emissions or zero emissions

Carbon dioxide removal technologies classification tree

Not exhaustive



Atmospheric CO_2 Management

Natural CO_2 cycle

Negative emission technologies

Zero / low emission technologies

Natural processes

Natural processes enhancers

Engineered processes

Biomass integration (photosynthesis)

Water dissolution (oceans, lakes, rivers)

Soils adsorption

Afforestation and reforestation[1]

CROPS[2]

Ocean fertilization

Artificial upwelling

Ocean alkalinity enhancement

Enhanced weathering

Soil carbon sequestration

Bioenergy + Biochar

Bioenergy + CCUS[3]

Direct Air Capture, Use and Sequestration

Bioenergy + CCU[3]

Direct Air Capture and Use

Fossil fuel + CCS[3]

🟧 Forestry-based
🟪 Ocean-based
🟦 Soil-based

Natural processes enhancers

🟩 Bioenergy
🟥 Direct air capture
⬜ Fossil fuel based

Engineered processes

1. Planting trees is classified as negative for the timescale studied, even if it is not fully permanent
2. CROPS is crop residue ocean permanent sequestration CCS refers to carbon capture and storage, which is usually capturing waste CO_2 from point sources (power plant or factory) and storing it in geological formations; CCU refers to carbon capture and use; CCUS refers to carbon capture, use and sequestration; some of the uses release the carbon in the atmosphere (agriculture, beverage, etc.) making the process carbon neutral, and some store it (concrete, plastics, etc.) making the process carbon negative; see our CCS FactBook for more information about CCS

Note: Other solutions such as wetland and coastal restoration (blue carbon) were not considered in this study

Source: A.T. Kearney Energy Transition Institute analysis

Negative emission technologies can be divided into five groups, depending on industry and natural process enhancement type

Main negative emission technologies grouped by category

1		Forestry-based	• Afforestation and reforestation • CROPS (capture)	Natural processes enhancers
2		Ocean-based	• CROPS (storage) • Ocean fertilization • Artificial upwelling	
3		Soil-based	• Enhanced weathering • Soil carbon sequestration	
4		Bioenergy	• Biochar • Bioenergy with CCS	Engineered processes
5		Direct air capture	• Active or passive collector device • Liquid, solid or organic-inorganic hybrid sorbent • Temperature, pressure or moisture swing adsorption	

Note: CROPS is crop residue ocean permanent sequestration. CCS is carbon capture and storage.
Source: A.T. Kearney Energy Transition Institute analysis

Cost and potential are not the only features that should be evaluated

Evaluation criteria of negative emission technologies

- A **FactCard** for each technology was developed and presented as described in the table on the right.
- Technologies were ranked based on **eight key features**, allowing for a thorough comparison,
- A small **pros and cons** enumeration was added on the bottom for technology-specific features.
- All results are summarized and analyzed at the end of the section.

Pros

- In this box, we list the advantages and benefits for all the technologies

Cons

- In this box, we list the disadvantages and downsides for all the technologies

Key features estimates		
Cost ($ per t-CO_2)	**Cost estimation for capturing one metric ton of CO_2**	🟩🟨🟥
Potential (Gt-CO_2 per year)	**Potential achievable by 2050 if the NET is globally deployed**	🟩🟨🟥
Water consumption (km^3 per Gt-CO_2)	**Quantity of water required to capture one metric ton of CO_2**	🟩🟨🟥
Risk of reversal	**If there is a risk that the carbon captured will be released back to the atmosphere**	🟩🟨🟥
Verifiability	**If it is possible to check and quantify if the carbon is effectively removed or not**	🟩🟨🟥
Thermal energy[1] (GJ per t-CO_2)	**Net thermal energy required for capturing one metric ton of CO_2**	🟩🟨🟥
Electrical energy[1] (kWh per t-CO_2)	**Net electrical energy required for capturing one metric ton of CO_2**	🟩🟨🟥
Land use (m^2 per t-CO_2 per year)	**Area of land required for capturing one metric ton of CO_2**	🟩🟨🟥

Advantage 🟩 🟨 🟥 **Drawback**

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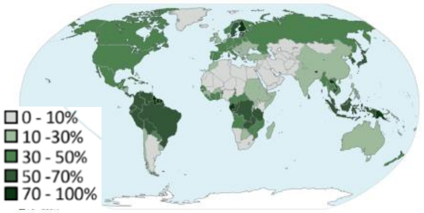
[1] Thermal and electrical energy consumption can lead to "leakage", depending on the source of energy. Leakage refers to GHG emissions that occur as a result of activities undertaken to mitigate or offset GHG emissions.

Source: A.T. Kearney Energy Transition Institute analysis

Afforestation and Reforestation: Fact Card



World map of forest area as a percent of land area
Image adapted from FAO, 2016.

- **Afforestation** refers to the **plantation of trees** on lands that historically have **not contained forests** (over the last 50 years in the context of the Kyoto Protocol)
- **Reforestation** is planting trees on land which were **initially forested** but contain now **less than 10%** of forest cover (due to human activity or natural perturbations)

Pros

- Low cost
- Mature
- No energy requirements

Cons

- Alters surface energy budget
- Change in hydrological cycle
- Land and water use competition with food supply and bioenergy
- Afforestation can damage existing ecosystems
- Possible "leakage", as it may increase deforestation, and/or lower timber prices and thus reduce investment, etc

- Different **species of trees** capture CO_2 at **different rates**. However, the most efficient way is often to plant the **appropriate species**, which is adapted to the local environment. So the **growth** will be **optimum** and the impact on the environment will be positive.
- Afforestation of grassland ecosystems or diversified agricultural landscapes with monocultures or invasive alien species can have negative **impacts on ecosystems and biodiversity** (while forest restauration with native species can be positive).

Key features estimates

Cost ($ per t-CO_2)	**$5–$50**	🟩
Potential (Gt-CO_2 per year)	**0.5–3.6[1]**	🟨
Water Consumption (km^3 per Gt-CO_2)	**92**	🟥
Risk of reversal	**Yes**	🟥
Verifiability	**Yes**	🟩
Thermal Energy (GJ per t-CO_2)	**0**	🟩
Electrical Energy (kWh per t-CO_2)	**0**	🟩
Land use (m^2 per t-CO_2 per year)	**800**	🟥

Advantage 🟩 🟨 🟥 **Drawback**

---

1. According to IPCC "SR1.5 – chapter 3" (2018). A much higher value of 23.8 $GtCO_2$ per year was suggested by Griscom et al, 2017. This value refers to 20 conservation, restoration and/or improved land management actions, which may not be restricted to afforestation and reforestation. Smith et al, 2015 have suggested 4 to 12 $GtCO_2$ per year

Sources: IPCC "SR1.5 – chapter 4" (2018); Map: Carbon Dioxide Removal Options: A Literature Review Identifying Carbon Removal Potentials and Costs, University of Michigan; FAO; A.T. Kearney Energy Transition Institute analysis

Afforestation projects have already started at large scale, particularly in China and Africa, but they must be increased to match the targets

Grain for Green (GfG)

- **China.** With the goal of **reconverting steep slopes** that had been cleared for **farming** to their original vegetation (forest or grassland), the GfC program was the **world's largest** reforestation program. Between 1999 and 2012, **24.86 million hectares** corresponding to more than **1.1 $GtCO_2$** (2009) were planted. In 2015, China pledged to increase its stock volume by 4.5 billion m3 over 2005 levels by 2030, translating into **8.25 $GtCO_2$**.

The African Forest Landscape Restoration Initiative (AFR100)

- **Africa.** AFR100 is a country-led effort to bring 100 million hectares of land in Africa into restoration by 2030. It aims to accelerate restoration to enhance food security, increase climate change resilience and mitigation, and combat rural poverty. **28 countries** and **113 Mha** of land committed in the effort that can capture **0.79 to 1.32 $GtCO_2$/year**. The initiative gets $1 billion from the World Bank and $481 million from nine private investors.

WWF, BirdLife International, and Wildlife Conservation Society

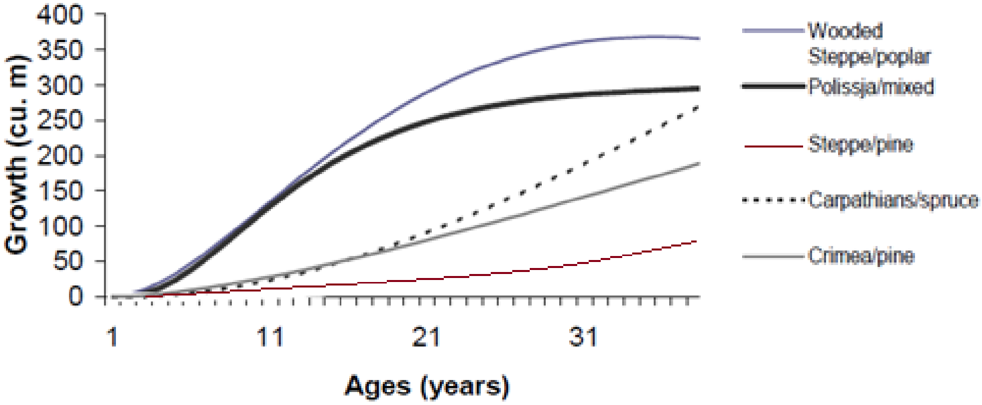
- **Trillion Trees.** Once home to more than 6 trillion trees, Earth only has 3 trillion today and keeps losing **10 billion per year**. Launched in 2017, this partnership between three of the world's largest conservation organizations set the goal to plant 1 trillion trees by 2050, in a 120-country unprecedented effort that can capture **132 to 183 Gt of CO_2** once the trees mature.

Sources: O. Delang, C. & Yuan, Z. (2015); Wolosin, M. (2017); World Economic Forum (2017); Trillion trees project; afr100.org; A.T. Kearney Energy Transition Institute analysis

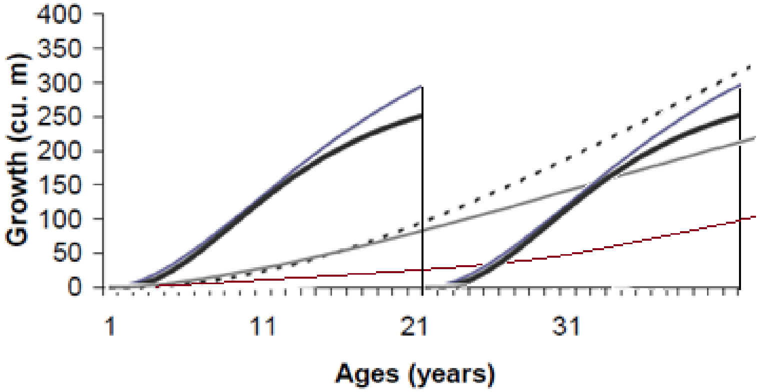
There are ways to optimize simple forestation by cutting and planting trees at the right time

Carbon is then stored in wood products, in the ocean, or in the soil thanks to BECCS or biochar to prevent from releasing

Growth by fast-growing tree species across regions in Ukraine



Growth by fast-growing tree species across regions in Ukraine if the trees are harvested when their growth decelerates

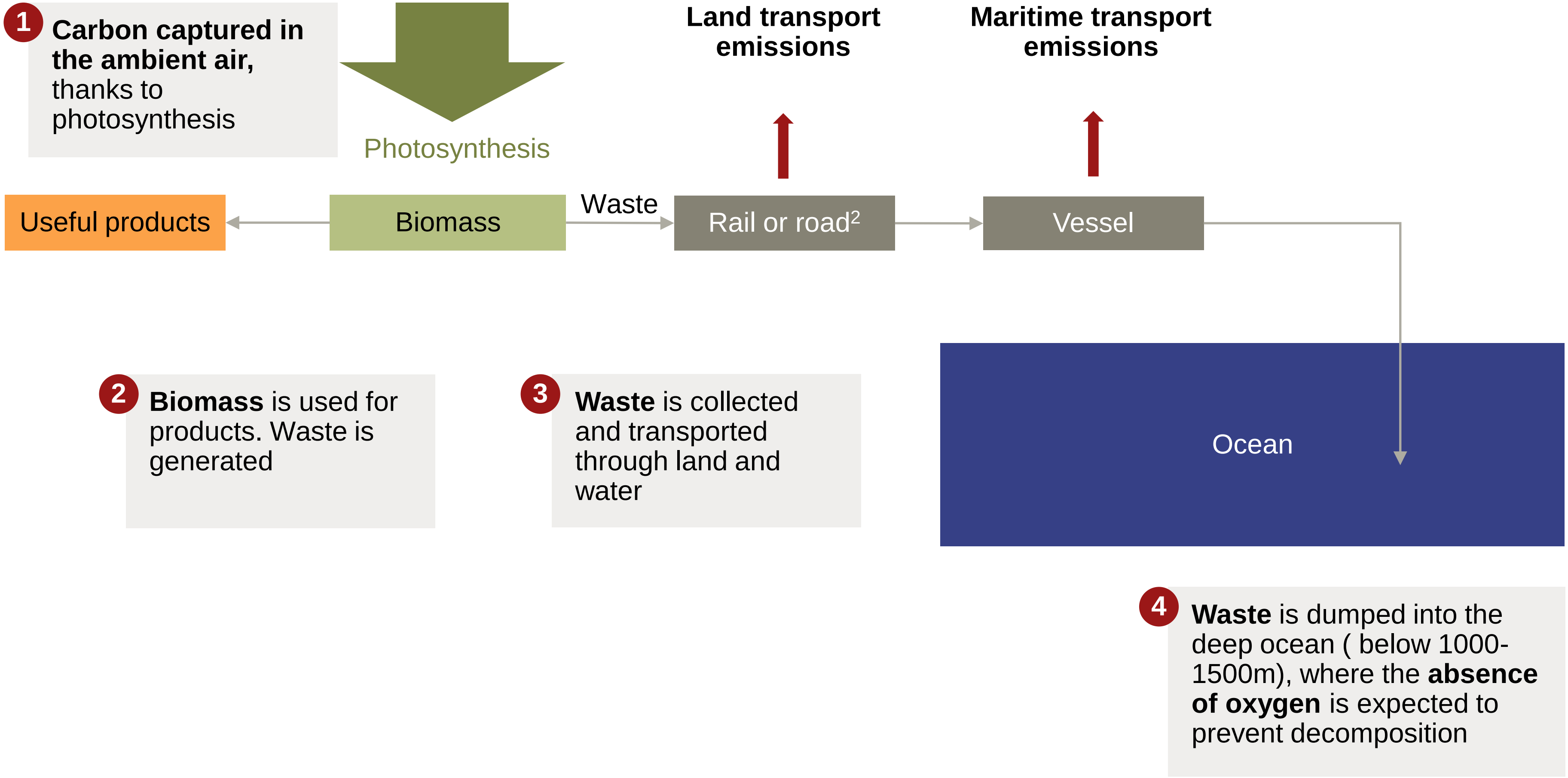


- When trees reach the culmination of their annual increment, they stop sequestering carbon. Indeed, forest carbon capture is the result of a **balance between growth of trees and carbon loss through decay.**
- For example, for the poplar, in 42 years, harvesting at the right time allows to have **600 m^3** of wood instead of less than **400 m^3** when not managed.
- Long-term management is planning to cut trees when they reach their **maximum annual increment** and finding a second life for the organic materials obtained. In this way, carbon can be captured at a higher rate, and cut wood and organic materials can be sold, reimbursing part of the fees employed.
- The organic materials obtained can be used in **wood products** (such as construction and furniture) and bioenergy (such as BECCS and biochar) or can be **stored in oceans** to achieve negative carbon emission.
- Long-term management helps **reduce costs** and avoid carbon emissions due to natural process, such as fire and deforestation.

Sources: Carbon Capture and Storage in Forests, 2010, Environmental Science and Technology, Maria Nijnik, James Hutton Institute; A.T. Kearney Energy Transition Institute analysis

Collecting, transporting and dumping unwanted biomass into the deep ocean can possibly prevent re-emission

Rationale for CROPS[1]



① **Carbon captured in the ambient air,** thanks to photosynthesis

Photosynthesis

Land transport emissions

Maritime transport emissions

Useful products

Biomass

Waste

Rail or road[2]

Vessel

Ocean

② **Biomass** is used for products. Waste is generated

③ **Waste** is collected and transported through land and water

④ **Waste** is dumped into the deep ocean (below 1000-1500m), where the **absence of oxygen** is expected to prevent decomposition

1. CROPS is crop residue ocean permanent sequestration
2. Trees are in some places directly transported through the rivers

Source: A.T. Kearney Energy Transition Institute analysis

Crop Residue Ocean Permanent Sequestration (CROPS): Fact Card

- **Storing biomass** (such as crop waste) underwater can be a cheap and effective solution to prevent re-emission from burning or decomposition.
- Burning re-emits all the carbon stored in the biomass.
- Due to fast decomposition, **soils** can only keep up to **10%** of the carbon present in the biomass after **20 years.**
- Extrapolating results from experiments done at a depth of 2625m, it is predicted that ocean sequestration could keep **75%** of the carbon present in the biomass after **100 years.**

Pros

- No competition in terms of land and water use

Cons

- Low scientific knowledge
- No field demonstrations of this approach
- Potential impact to marine ecosystem
- May violate the London Convention of the Seas as active dumping
- Transportation costs

Key features estimates

Cost (\$ per t-CO_2)	**\$50–\$94[1]**	🟨
Potential (Gt-CO_2 per year)	**0.7–1**	🟥
Water Consumption (km^3 per Gt-CO_2)	**0**	🟩
Risk of reversal	**To study**	🟨
Verifiability	**Yes**	🟩
Thermal Energy (GJ per t-CO_2)	**Transport**	🟨
Electrical Energy (MWh per t-CO_2)	**0**	🟩
Land use (m^2 per t-CO_2 per year)	**0**	🟩

Advantage 🟩 🟨 🟥 **Drawback**

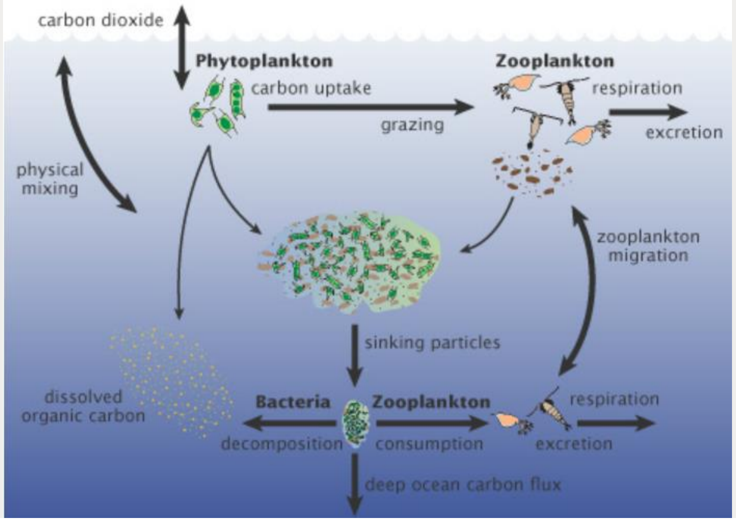
---

1. The lower estimate assumes \$20 per ton CO_2 for collecting and getting the crop residue ready for transport and \$30 per tonCO_2 for transport. The higher estimate gives the final cost without making such distinction but mentioning the assumption of 4,000 km boat transport.

Note: Illustrative image shows logs from the 1800's and early 1900's well preserved even at shallow icy and low oxygen waters of the Great Lakes

Sources: Bronson, D., et. al (2011); G. Keil, R., et al (2010); A. Metzger, R., & Benford, G. (2001); E. Strand, S. & Benford, G. (2009); A.T. Kearney Energy Transition Institute analysis

Ocean Fertilization: Fact Card



- Ocean fertilization is adding nutrients that **boost phytoplankton activity in oceans**. Consequently, more carbon is moved to the deep ocean through the **biological pump**, so the carbon concentration is lower in the upper layer. Consequently, more carbon can be absorbed by the ocean at the surface.
- Three nutrients are limiting phytoplankton growth: iron, nitrogen, and phosphorous. Most of the time, the one that is lacking is **iron**. This process is only **speculative** and has never been tested at large scale.

Pros

- High potential
- No competition in terms of land, energy and water use

Cons

- Low scientific knowledge
- No field demonstrations of this approach
- Change in natural cycles
- May violate the London Convention of the Seas as active dumping

Key features estimates

Cost (\$ per t-CO_2)	**\$23–\$111**[1]	🟨
Potential (Gt-CO_2 per year)	**2.6–6.2**[2]	🟩
Water Consumption (km^3 per Gt-CO_2)	**0**	🟩
Risk of reversal	**To study**	🟨
Verifiability	**To study**	🟨
Thermal Energy (GJ per t-CO_2)	**Mining and transport**	🟨
Electrical Energy (MWh per t-CO_2)	**0**	🟩
Land use (m^2 per t-CO_2 per year)	**0**	🟩

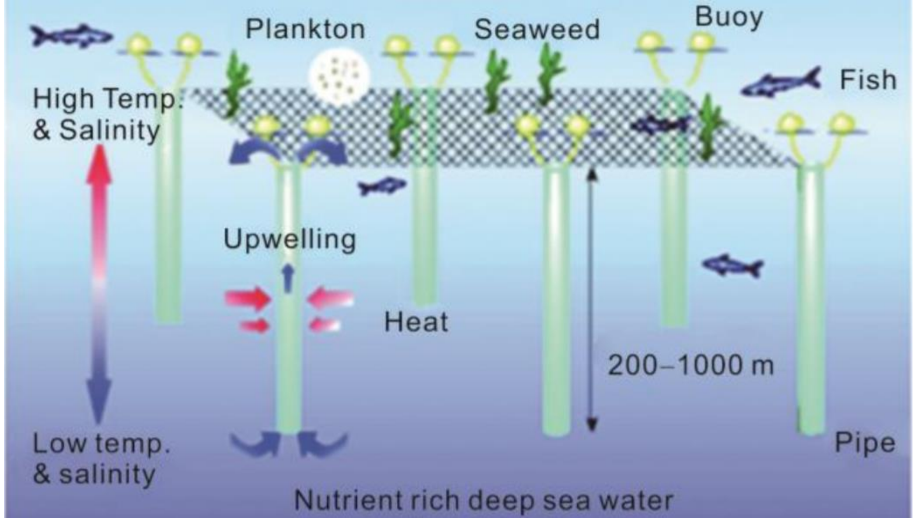
Advantage 🟩 🟨 🟥 **Drawback**

---

1. Based on a quartile analysis from all sources, 50% of the estimates suggest ocean fertilization costs between \$23 and \$111 per t-CO_2.
2. Using a quartile analysis, 50% of the sources suggest that ocean fertilization could sequester and store between 2.6 and 6.2 $GtCO_2e$ per year.

Source: Carbon Dioxide Removal Options: A Literature Review Identifying Carbon Removal Potentials and Costs, University of Michigan;
Image: earthobservatory.nasa.gov/Features/Phytoplankton; A.T. Kearney Energy Transition Institute analysis

Artificial Upwelling: Fact Card



- Another way to achieve ocean fertilization is by **pumping nutrient-rich water** from the sub-surface ocean **(200 to 1,000 m)** to the surface
- Although this process would release some of the CO_2 stored in the intermediate and deep sea, the overall enhancement of the **biological pump** would be expected to contribute to a **higher oceanic carbon uptake.**
- Vertical motion is achieved **passively** by salinity and temperature differences and/or wave energy or **actively** by electrical pumps or air lift (injecting bubbles).

Pros

- No competition in terms of land and water use

Cons

- Very low scientific knowledge
- No field demonstrations of this approach
- Expected reversal if stopped
- Disturbance to regional balances
- Oceans' responsibility legal issues

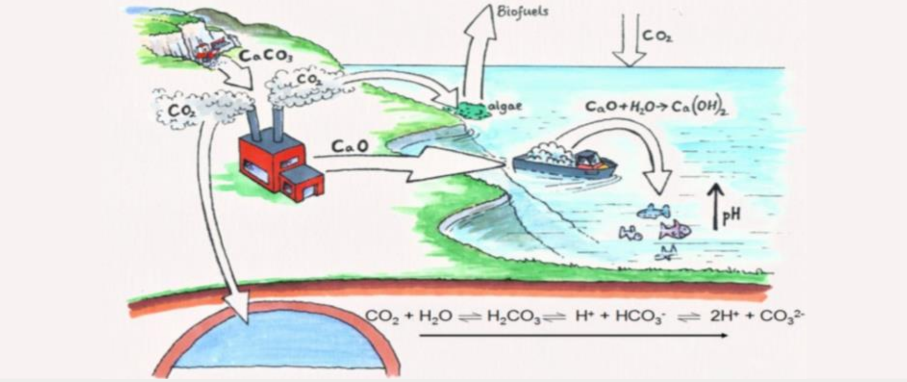
Key features estimates

Cost (\$ per t-CO_2)	**N/A (high)**	🟥
Potential (Gt-CO_2 per year)	**0–0.9 Gt-CO_2 per year**	🟥
Water Consumption (km^3 per Gt-CO_2)	**0**	🟩
Risk of reversal	**Yes**	🟥
Verifiability	**To study**	🟨
Thermal Energy (GJ per t-CO_2)	**0–N/A**	🟨
Electrical Energy (MWh per t-CO_2)	**0–N/A**	🟨
Land use (m^2 per t-CO_2 per year)	**0**	🟩

Advantage 🟩 🟨 🟥 **Drawback**

Sources: Oschlies, A., et al (2010); Salomon, M., & Markus, T. (2018); UNEP (2012); Bauman, S.J., et al (2014); IPCC AR5 Chapter 6; Pan, Y., et al. (2015); A.T. Kearney Energy Transition Institute analysis

Ocean Alkalinity Enhancement: Fact Card



- **1st step:** calcination of **limestone** ($CaCO_3$) into **lime** (calcium oxide, CaO) and storage of CO_2
- **2nd step:** Hydration of lime into calcium hydroxide $Ca(OH)_2$, which is put into the ocean, effectively shifting the equilibria equations to the right

Pros	Cons
• Fights ocean acidification • No competition in terms of land and water use • Electrolysis of sea water also produces hydrogen	• Low scientific knowledge • Requires massive mining activity • Possible release of heavy metals • Possible disturbance of ocean biogeochemical functioning • May violate the London Convention of the Seas as active dumping

- The addition of alkaline materials to sea water fights **ocean acidification** and draws carbon dioxide from the atmosphere
- The most commonly proposed approach is called **ocean liming** and consists of introducing calcium ions into ocean water by adding calcium oxide or calcium hydroxide. This approach is represented on the left, and has a very energy intensive first step.
- Other approaches include **electrolysis** of sea water and **weathering** of silicate and carbonate minerals on land[1]

Key features estimates

Cost (\$ per t-CO_2)	**\$10-\$600**	🟨
Potential (Gt-CO_2 per year)	**2-20**	🟩
Water Consumption (km^3 per Gt-CO_2)	**0**	🟩
Risk of reversal	**To study**	🟨
Verifiability	**To study**	🟨
Thermal Energy (GJ per t-CO_2)	**3.2-5.9**	🟨
Electrical Energy (MWh per t-CO_2)	**~119**	🟥
Land use (m^2 per t-CO_2 per year)	**0**	🟩

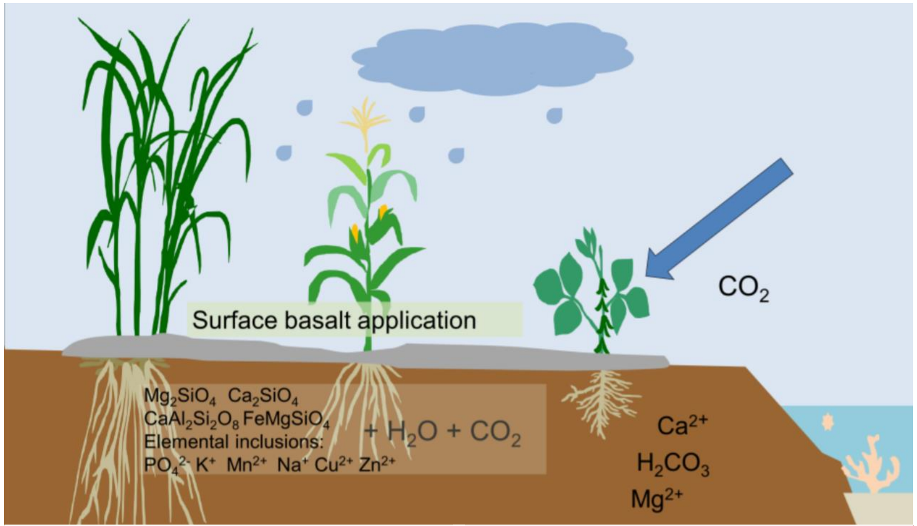
Advantage 🟩 🟨 🟥 **Drawback**

---

1. Please refer to the Terrestrial Enhanced Weathering FactCard

Sources: IPPC "SR1.5 – chapter 3 and 4" (2018); Kruger, T. (2010); Renforth, P. (2012); Renforth, P. & Henderson, G. (2017); ICEF2018 Roadmap: Direct Air Capture of Carbon Dioxide; UNEP (2017)

Terrestrial Enhanced Weathering: Fact Card



Pros

- Reduced soil acidification, and possibly ocean acidification by alkaline runoff.
- EW with basalt has long been practiced on small scale
- Possibility for increased food production and soil improvement by release of phosphorous by weathering of basalts

Cons

- High expected costs
- Requires massive mining activity
- Small silicate rock particles can cause silicosis if inhaled
- Possible impact on natural cycles (soil microbial biodiversity; particles washed into rivers and oceans may decrease water clarity; possible modification in hydrological soil properties; possible release of heavy metals, mainly by olivine-rich rocks; etc)

- **Weathering** is the natural process of rock decomposition via chemical and physical processes in which CO_2 is **spontaneously consumed** and converted to solid or dissolved alkaline bicarbonates and/or carbonates.
- Silicate rock material containing calcium or magnesium (e.g. basalts) suffers weathering. This process can be accelerated by augmenting the surface area exposed.
- Several approaches are possible, but the most pragmatic is considered to be spreading fine-grained rock dust over croplands, which also has co-benefits for agriculture.

Key features estimates

Cost (\$ per t-CO_2)	**\$50–\$200**[1]	🟥
Potential (Gt-CO_2 per year)	**2–4**	🟨
Water Consumption (km^3 per Gt-CO_2)	**0.4**	🟨
Risk of reversal	**No**	🟩
Verifiability	**Yes**	🟩
Thermal Energy (GJ per t-CO_2)	**Transport and grinding**	🟨
Electrical Energy (MWh per t-CO_2)	**N/A**	🟨
Land use (m^2 per t-CO_2 per year)	**30**	🟨

Advantage 🟩 🟨 🟥 **Drawback**

---

1. The main costs are finding, transporting, and grinding the required rock material.

Sources: The Royal Society (2018); IPPC “SR1.5 – chapter 3 and 4” (2018); Strefler, J. et al. (2018); ICEF2018 Roadmap: Direct Air Capture of Carbon Dioxide;
Image: https://rockdustlocal.com/uploads/3/4/3/4/34349856/rdl_energy_farm_basalt_flyer_.pdf; A.T. Kearney Energy Transition Institute analysis

Soil Carbon Sequestration: Fact Card

- As seen in the previous section, soils already hold 46% of the land carbon.
- Soil carbon sequestration occurs when **the change in land management** increases the soil organic carbon content, resulting in a net removal from the atmosphere.
- Due to co-benefits in agriculture, some practices are already **cost-effective** in a few places even without supportive climate policy, translating into negative carbon capture costs.

Pros

- Low cost
- High potential
- No competition in terms of land and water use
- Better nutrient and food security

Cons

- Possible reversal if poor management practices resume
- Soil saturation after 10 to 100 years
- Possible “leakage” (e.g. by replacing cropping land use by perennial pasture, there could be considerable emissions from the new livestock grazing this pasture)

Key features estimates

Cost (\$ per t-CO_2)	**\$-45–\$100**	🟩
Potential (Gt-CO_2 per year)	**2.3–5[1]**	🟨
Water Consumption (km^3 per Gt-CO_2)	**0**	🟩
Risk of reversal	**Yes**	🟥
Verifiability	**No**	🟥
Thermal Energy (GJ per t-CO_2)	**0**	🟩
Electrical Energy (MWh per t-CO_2)	**0**	🟩
Land use (m² per t-CO_2 per year)	**0**	🟩

Advantage 🟩 🟨 🟥 **Drawback**

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1. According to UNEP (2017), “Most of the annual estimates are based on sequestration values calculated over 20 years. Given that sinks saturate, annualized sequestration estimates should be multiplied by 20 to derive the total cumulative sequestration potential”, or divided by ~4 to derive the average yearly potential until 2100

Sources: IPCC SR1.5 Chapter 3; UNEP (2017); Tas Thamo & David J. Pannell (2015); A.T. Kearney Energy Transition Institute analysis

Some soil management practices could have big potential for carbon capture while reducing erosion and improving fertility

Selected agricultural soil carbon sequestration practices[1]

Practice	**Agroforestry**	**Cover crops**	**No-till farming**
Description	 • Agroforestry refers to the practice of **growing trees** in crop or pasture fields. • Several systems have been tested in different locations, with sequestration rates reaching **15.2 ton CO_2 ha^{-1} year.**[1] • In addition to improved carbon uptake, benefits include reduced erosion, increased soil fertility, and better drought resistance.	 • Cover crops in crop fields are grown during the off season for **soil protection and enrichment.** • Global warming mitigation was calculated to be in the range of **10 to 15 ton CO_2e ha^{-1} year^{-1}**, coming not only from soil carbon sequestration, but also from other synergies such as the plantation of legume cover crops. • Reduced erosion, nitrogen fixation, and increased fertility are also among the advantages of cover crops utilization.	 • **Tillage** is the process of agricultural soil preparation through mechanical agitation (digging, stirring, and overturning). • Several conservation tillage methods exist, with **no-till farming** being subject to various studies. • Tests in China and Brazil have shown results between **3.1 and 9.8 ton CO_2 per ha^{-1} year.**[1] • Other benefits include lower operating costs and higher soil water retention.

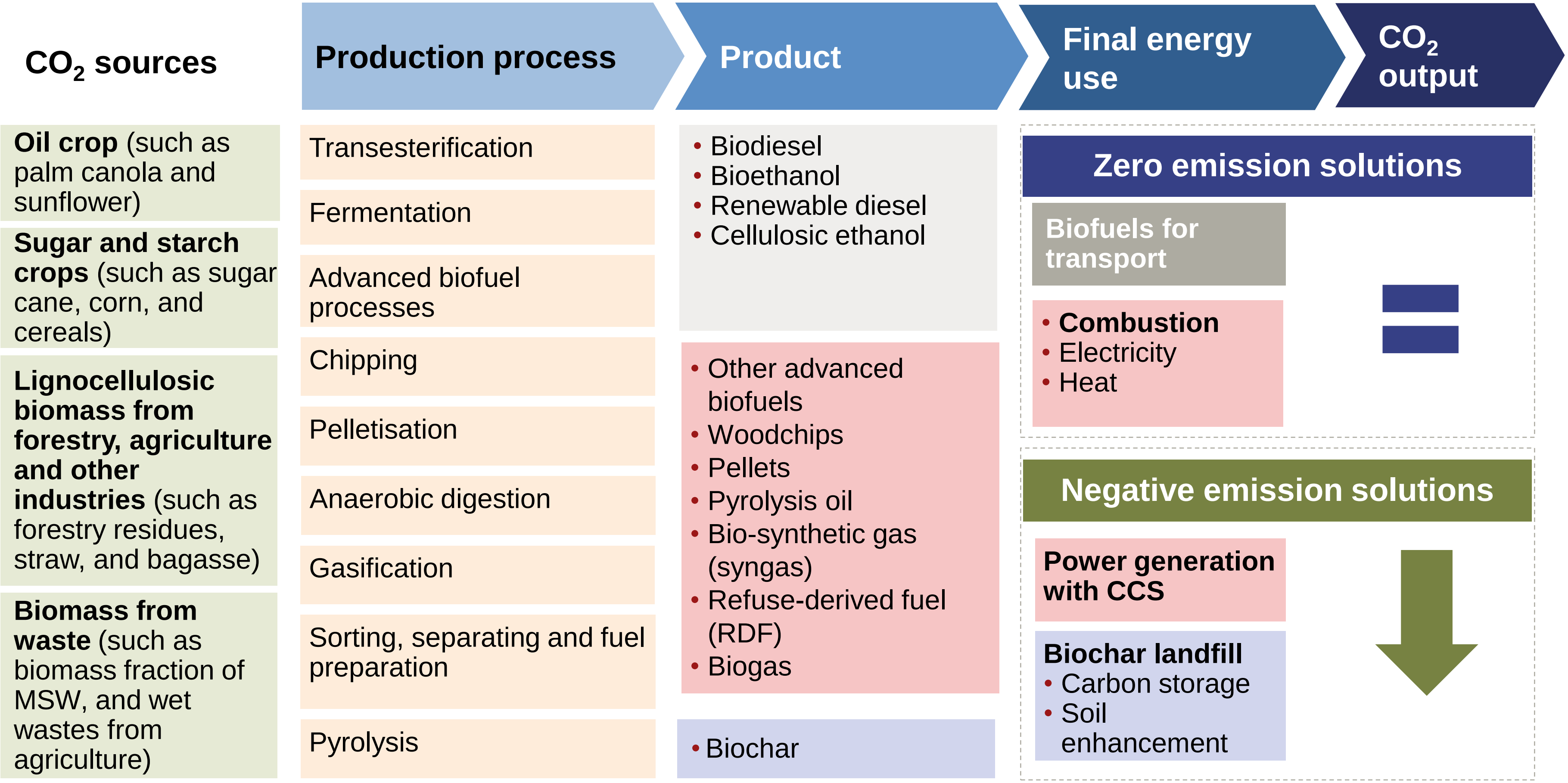
---

1. Other agricultural practices include grazing optimization and planting of legumes in grazing lands. Non-agricultural practices include desertification control and degraded land restoration.

Sources: Lorenz & K., Lal, R. (2014); P. Kaye, J., Quemada, M. (2017); Lu, X. et al (2018); Corbeels, M. et al (2016); A.T. Kearney Energy Transition Institute analysis

Bioenergy is usually carbon neutral, but it can be negative when biochar is stored in the soil or when used with CCS

Bioenergy value chain



CO_2 sources

- **Oil crop** (such as palm canola and sunflower)
- **Sugar and starch crops** (such as sugar cane, corn, and cereals)
- **Lignocellulosic biomass from forestry, agriculture and other industries** (such as forestry residues, straw, and bagasse)
- **Biomass from waste** (such as biomass fraction of MSW, and wet wastes from agriculture)

Production process

- Transesterification
- Fermentation
- Advanced biofuel processes
- Chipping
- Pelletisation
- Anaerobic digestion
- Gasification
- Sorting, separating and fuel preparation
- Pyrolysis

Product

- Biodiesel
- Bioethanol
- Renewable diesel
- Cellulosic ethanol

- Other advanced biofuels
- Woodchips
- Pellets
- Pyrolysis oil
- Bio-synthetic gas (syngas)
- Refuse-derived fuel (RDF)
- Biogas

- Biochar

Final energy use

CO_2 output

Zero emission solutions

Biofuels for transport

- **Combustion**
- Electricity
- Heat

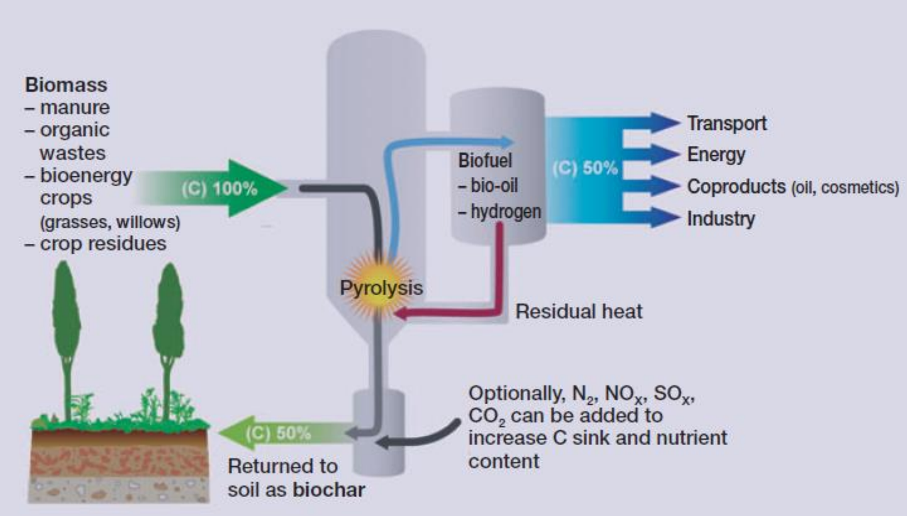
Negative emission solutions

Power generation with CCS

Biochar landfill
- Carbon storage
- Soil enhancement

Sources: IEA and FAO, 2017, How2Guide for Bioenergy, www.iea.org/publications/freepublications/publication/How2GuideforBioenergyRoadmapDevelopmentandImplementation.pdf; A.T. Kearney Energy Transition Institute analysis

Biochar: Fact Card



- **Biochar** is a kind of charcoal produced from biomass, such as crop or agricultural waste, thanks to **pyrolysis** (heating without combustion to around **300°–800°C**).
- Biochar's **decomposition is much slower** than the surrounding organic material. Consequently, it allows storing carbon in the **soil** for centuries.
- Biochar is also used in agriculture for its ability to **improve soil productivity**. It increases pH, thus benefiting acidic soils and improving water and nutrient retention.

Pros

- Already used for millenniums
- Positive side effect on nutrients and reduction of N_2O emissions
- Allows capturing CO_2 by photosynthesis while creating bio-energy

Cons

- Land competition
- Constrained by the maximum safe holding capacity of soils and limited biomass feedstock
- Uncertainties about carbon half-life bring potential risk of reversal
- Negative effects on soils can occur if the pH of the soil and the biochar are not well-matched

Key features estimates

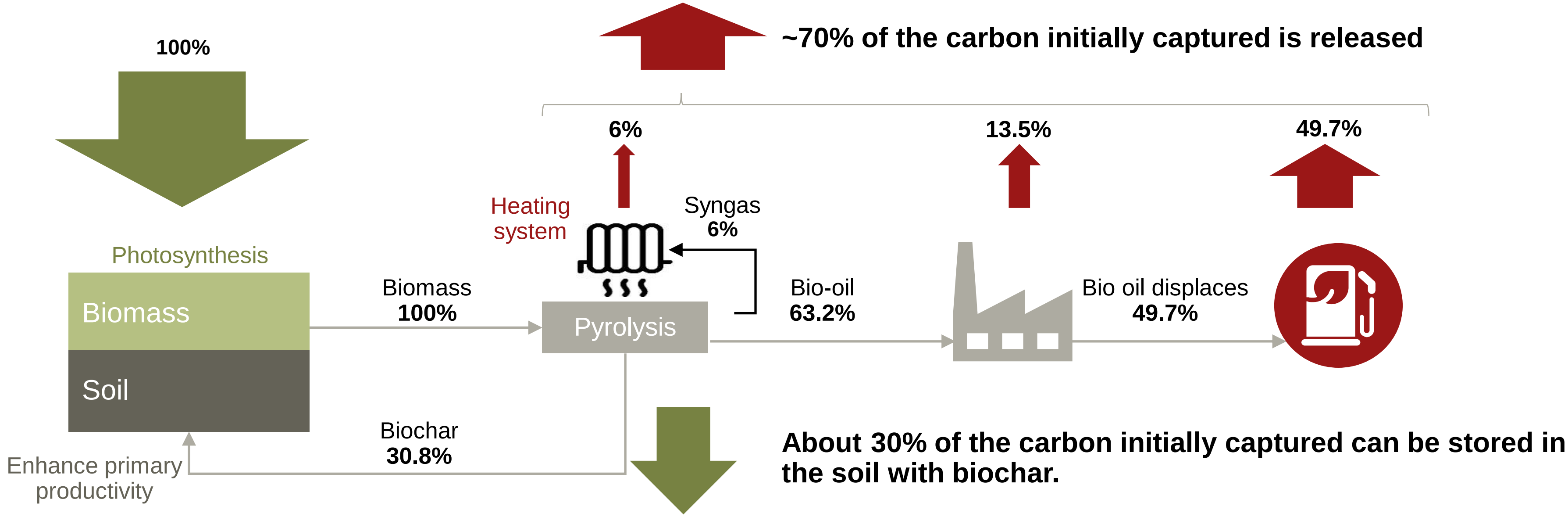
Cost (\$ per t-CO_2)	**\$30–\$120**	🟨
Potential (Gt-CO_2 per year)	**0.3–2**	🟨
Water Consumption (km^3 per Gt-CO_2)	**0 (for pyrolysis)**	🟩
Risk of reversal	**To study**	🟨
Verifiability	**Yes**	🟩
Thermal Energy (GJ per t-CO_2)	**<0**	🟩
Electrical Energy (MWh per t-CO_2)	**0**	🟩
Land use (m^2 per t-CO_2 per year)	**160–1,000**	🟥

Advantage 🟩 🟨 🟥 **Drawback**

Sources: IPCC "SR1.5 – chapter 3 and 4" (2018); image courtesy of Johannes Lehmann, Cornell University; A.T. Kearney Energy Transition Institute analysis

Energy produced from bioenergy and combined with biochar can lead to 30 percent carbon removal

Carbon balance of bioenergy with biochar storage


~70% of the carbon initially captured is released

About 30% of the carbon initially captured can be stored in the soil with biochar.

1 **Carbon captured in the ambient air** thanks to photosynthesis

2 **Pyrolysis of biomass.** The heating system operates with syngas obtained from pyrolysis.

3 **Centralized refinery.** Bio-oil is transported and refined to be usable. The process consumes around 20% of the carbon.

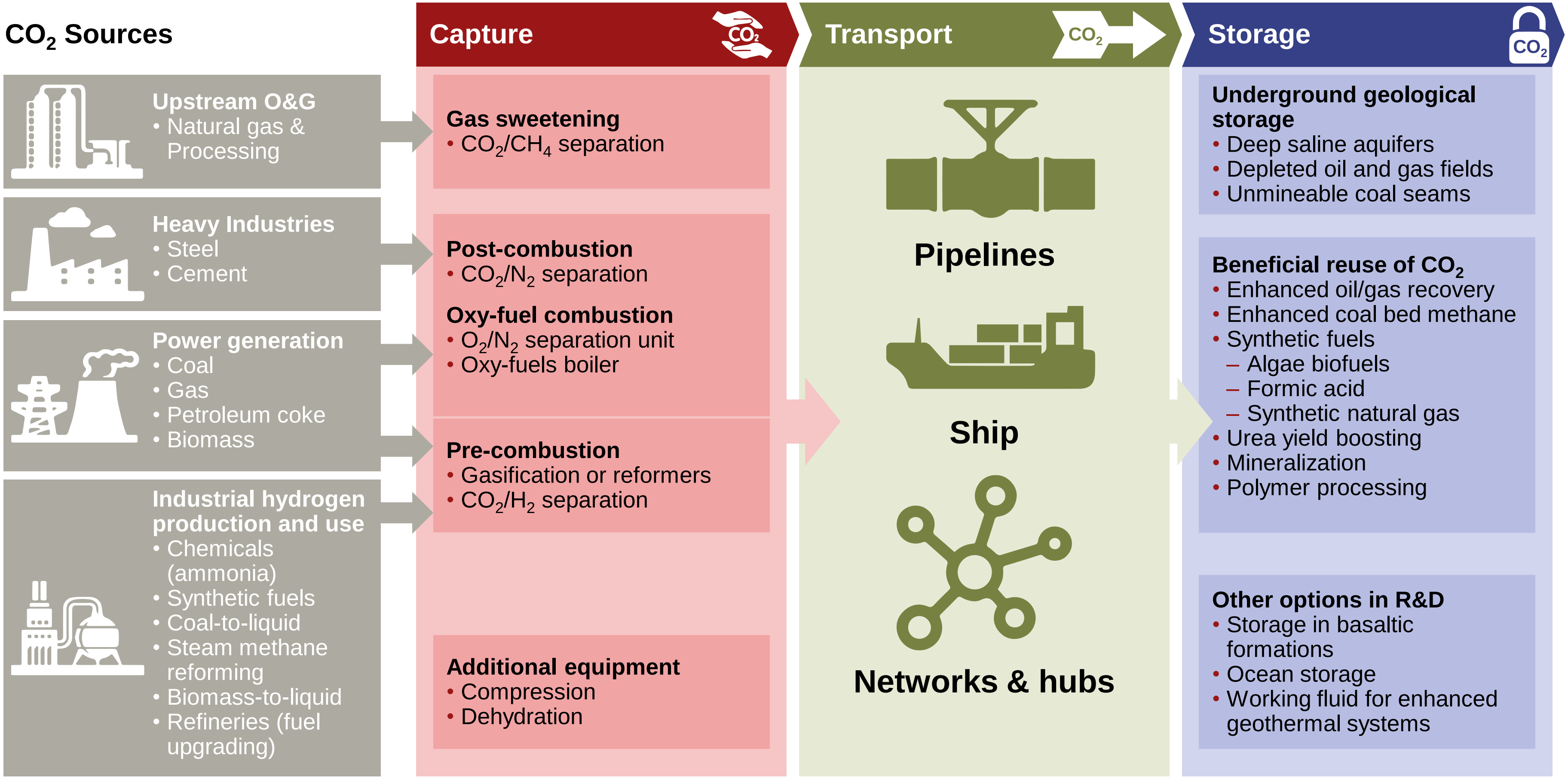
4 **Consumers.** The biofuel obtained is used directly for transport, electricity generation, or heating.

- **Biochar** is a stable solid rich in carbon (charcoal), resulting from the pyrolysis of biomass, which makes it **very stable**
- It is used as a **soil amendment** and can replace fertilizers

Sources: "The Charcoal Vision," Volume 100, Issue 1, Agronomy Journal, 2008; A.T. Kearney Energy Transition Institute analysis

CCS refers to a set of CO_2 capture, transport, and storage technologies that are combined to abate emissions from stationary CO_2 sources

CCS value chain



CO_2 Sources

Upstream O&G
- Natural gas & Processing

Heavy Industries
- Steel
- Cement

Power generation
- Coal
- Gas
- Petroleum coke
- Biomass

Industrial hydrogen production and use
- Chemicals (ammonia)
- Synthetic fuels
- Coal-to-liquid
- Steam methane reforming
- Biomass-to-liquid
- Refineries (fuel upgrading)

Capture

Gas sweetening
- CO_2/CH_4 separation

Post-combustion
- CO_2/N_2 separation

Oxy-fuel combustion
- O_2/N_2 separation unit
- Oxy-fuels boiler

Pre-combustion
- Gasification or reformers
- CO_2/H_2 separation

Additional equipment
- Compression
- Dehydration

Transport

Pipelines

Ship

Networks & hubs

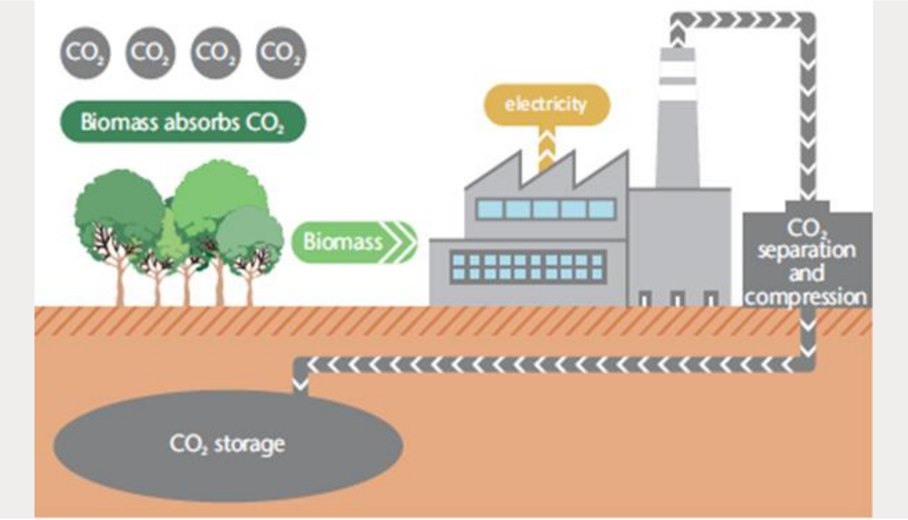
Storage

Underground geological storage
- Deep saline aquifers
- Depleted oil and gas fields
- Unmineable coal seams

Beneficial reuse of CO_2
- Enhanced oil/gas recovery
- Enhanced coal bed methane
- Synthetic fuels
  - Algae biofuels
  - Formic acid
  - Synthetic natural gas
- Urea yield boosting
- Mineralization
- Polymer processing

Other options in R&D
- Storage in basaltic formations
- Ocean storage
- Working fluid for enhanced geothermal systems

BECCS: Fact Card



- CCS used in the framework of bioenergy represents both a negative carbon solution and a way of producing sustainable energy.
- **CO_2 is captured during bioenergy combustion** or in the **manufacture of biofuels** and can be then **stored** or used.
- A few pilot plants of BECCS are already producing electricity while storing carbon, but mostly at **small scale.**

Pros

- Mature technology
- Provides both sustainable energy and negative carbon emission

Cons

- High cost
- Land competition
- Competitiveness on energy price
- Significant efficiency penalties cause the failure of many projects

Key features estimates

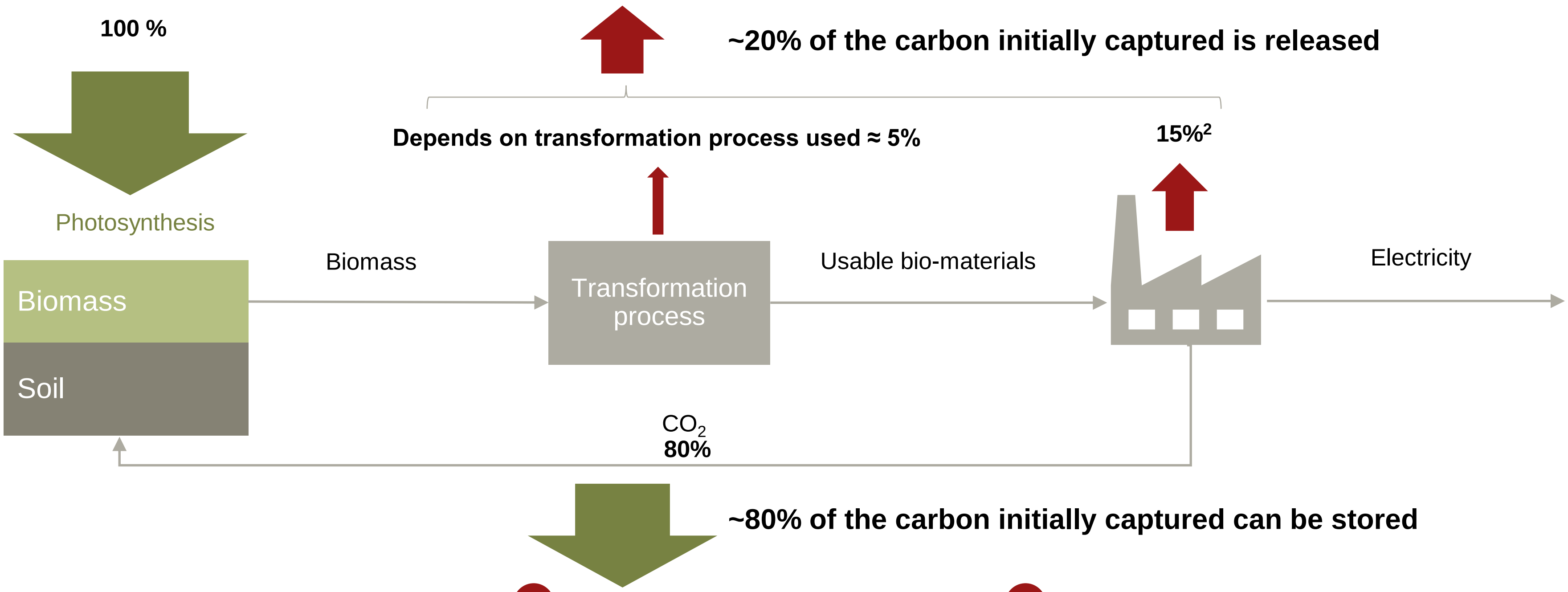
Cost (\$ per t-CO_2)	**\$100 to \$200**	🟥
Potential (Gt-CO_2 per year)	**0.5–5**	🟨
Water Consumption (km^3 per Gt-CO_2)	**60**	🟥
Risk of reversal	**Dependent on storage**	🟨
Verifiability	**Yes**	🟩
Thermal Energy (GJ per t-CO_2)	**<0**	🟩
Electrical Energy (MWh per t-CO_2)	**<0**	🟩
Land use (m^2 per t-CO_2 per year)	**310–580**	🟥

Advantage 🟩 🟨 🟥 **Drawback**

Sources: "Technology Roadmap Delivering Sustainable Bioenergy," IPPC "SR1.5 – chapter 3 and 4" (2018); A.T. Kearney Energy Transition Institute analysis

Energy produced from bioenergy and combined with CCS can lead to about 80 percent carbon removal[1]

Carbon balance of bioenergy with CCS



100 %

Photosynthesis

Biomass

Soil

Biomass

Transformation process

Depends on transformation process used ≈ 5%

~20% of the carbon initially captured is released

Usable bio-materials

15%[2]

Electricity

CO_2
80%

~80% of the carbon initially captured can be stored

① **Carbon captured in the ambient air,** thanks to photosynthesis

② **Transformation process,** providing materials ready for power plants

③ **Power plant with CCS,** electricity generation while carbon is captured and stored

It can also be applied during the **manufacture of biofuels.**

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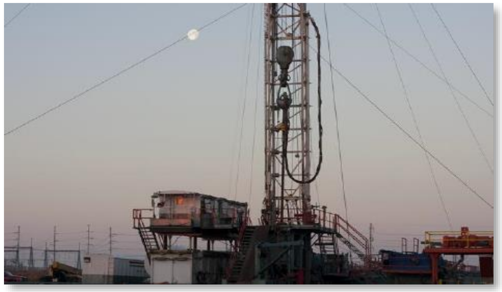
1. Calculations realized with a rate of carbon capture equal to 85%
2. Depending on CO_2 capture efficiency, some CO_2 is released.

Source: A.T. Kearney Energy Transition Institute analysis

CCS technologies are already operating in a few bioenergy plants in the US, Canada, and Netherlands

All projects have an ethanol plant as the CO_2 source



Decatur, Illinois (US) / November 2011

- **Archer Daniels Midland Company.** First large-scale project that combines CO_2 capture and storage with bioenergy production. The plant captures **1 $MtCO_2$ per year** from the distillation of corn into bioethanol. CO_2 is compressed, dehydrated, and injected on site for **permanent storage.** This project received a **\$140 million** subsidy from the US Department of Energy.

Lloydminster (Canada) / 2012

- **Husky Energy. 250 tons of CO_2 per day** are compressed and transported from an ethanol plant in Saskatchewan to nearby Lashburn and Tangleflags oil fields for **enhanced oil recovery** by tanker. The federal government's ecoENERGY Technology Initiative gave a **\$14.5 million** subsidy to Husky to develop and demonstrate the efficiency of capture and storage technologies.

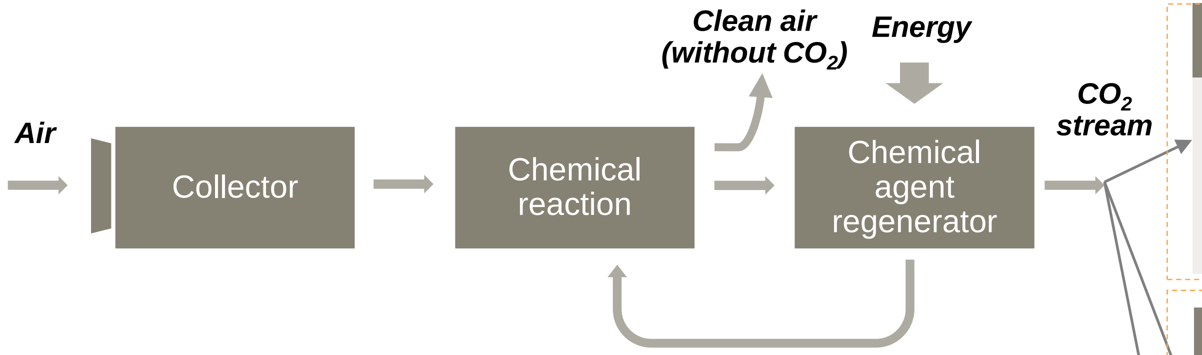
Russel, Kansas (USA) / 2003–2005

- **University of Kansas.** First project completed to combine bioenergy with CCS. The CO_2 from an ethanol plant was compressed, liquefied, and transported to the injection well for enhanced oil recovery. A total of **7,700 tCO_2** was injected, increasing the oil production by about **27,900 barrels.** It was the first project to demonstrate BECCS, although it was considered as a failure in terms of EOR.

Sources: IEA "Technology Roadmap Delivering Sustainable Bioenergy"; Bioenergy and Carbon Capture and Storage, March 2019, Global CCS Institute, Christopher Consoli; A.T. Kearney Energy Transition Institute analysis

Direct air capture systems are an emerging class of technologies able to separate CO_2 directly from ambient air

Direct air capture principle



Carbon storage

- Underground geological storage
  - Deep saline aquifers
  - Depleted oil and gas fields
  - Unmineable coal seams
- Storage in basaltic formations
- Ocean storage

Negative emissions solutions

Transformation

- Manufacturing of synthetic fuels
- Manufacturing of chemical and materials (organic chemistry, minerals)

Direct use

- Food and carbonated drinks
- Boost agriculture

Zero emissions solutions

① **Collecting ambient air** is achieved with a mechanical device that brings air from the atmosphere to the chemical agent.

② The **reacting phase** represents the chemical reaction between the CO_2 and the chemical agent. Purified air is released in the atmosphere.

③ The **regeneration phase** is where the CO_2 is released from the chemical agent. The agent can be reused, and the CO_2 produced can be used or stored.

- This kind of technology is not totally new because such systems have been implemented in **submarines** and **space applications** for decades.
- **Low concentration of CO_2 in ambient air** increases DAC **cost** and decreases DAC efficiency compared to CCS
- There are different kind of mechanical device to capture carbon in the air using different methods to pass air into the filter and different absorbents to capture and concentrate CO_2

Sources: Carbon180 Fact Sheet, "Carbon Sequestration through Direct Air Capture"; ICEF Roadmap 2018 “Direct Air Capture of Carbon Dioxide” (Dec. 2018); A.T. Kearney Energy Transition Institute analysis

DAC installations already offer solutions to get local carbon on demand to manufacturing

Hinwil (Canton of Zurich, Switzerland) **/ May 31, 2017**

- **Climeworks**. The first commercial plant that allows industrials to capture on-demand carbon in the atmosphere and use it for industrial needs. The plant is getting **900 tons of CO_2 annually** and is provisioning a greenhouse to **boost vegetables growth**. The plant is powered by waste recovery facility.

ASU's Polytechnic Campus (US)

- **Arizona State University**. Integrating the novel CO_2-capture and delivery technologies, ASU was able to boost microalgae productivity, ultimately achieving a better cost-effectiveness. In a 1,500-liter raceway pond, this is the first prototype to feed algae biomass,

Huntsville, Alabama (US) **/ 2018**

- **Global thermostat**. The firm's first commercial plant is expected to extract carbon at a forecasted operative cost of **\$150 per ton of CO_2**. The CO_2 will be directly used to provide bottlers.

Sources: Climeworks, www.climeworks.com/wp-content/uploads/2017/05/01_PR-Climeworks-DAC-Plant-Opening.pdf, ASU, cnce.engineering.asu.edu/project/project-2-title, Global Thermostat, carbonalist.com/2017-carbon-a-list; A.T. Kearney Energy Transition Institute analysis

Technologies use various ranges of systems for each module

Each system on the market is a combination of the following technologies:

Collector

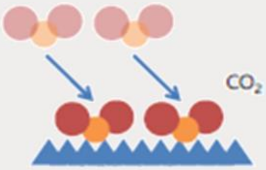
- **Air contractor with a set of fans that move air through the disposal**
- **Passive device that exploits natural wind**

How the sorbents are brought into contact with ambient air. This is done using an air collector. The structural materials, geometric design, pressure drop, and other features of the air collector are important challenges for DAC designs and dominate capital costs.

Chemical reaction

- **Liquid solvent (aqueous hydroxides, solid supported amines, and solid alkali carbonates)**
- **Solid sorbent (solid alkali carbonates), the most used on the market**
- **Organic-inorganic hybrid sorbent**

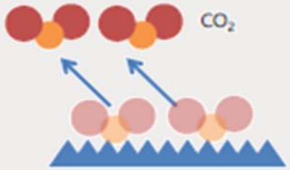
CO_2 in the air reacts with a chemical agent, temporarily creating a new molecule. The choice of the chemical agent is an extremely important part of DAC system design since it determines most other aspects of the overall system. For economic reasons, chemical agents must be used many times.



Chemical agent regenerator

- **Temperature-swing adsorption (increasing the temperature of the solution)**
- **Pressure-swing adsorptions (increasing the pressure of the solution)**
- **Moisture-swing adsorption (increasing the humidity of the solution)**

It is the stage of releasing captured CO_2 from the chemical reaction. Energy is added to the system, so the chemical agent used to capture CO_2 can be reused to capture more CO_2 in the air, and the CO_2 captured is released to be stored or used.

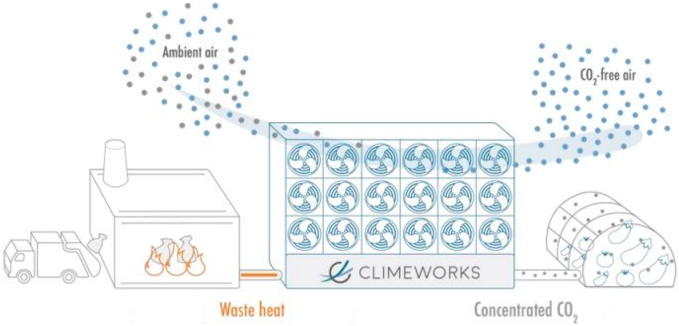


Sources: ICEF2018 Roadmap: Direct Air Capture of Carbon Dioxide; Sanz-Pérez E. et al. (2016), Chemical Reviews; A.T. Kearney Energy Transition Institute analysis

DAC with active collector–solid sorbent–hybrid temperature and pressure-swing adsorption: Fact Card

Climeworks (Zürich, Switzerland)

Collector	Set of fans that move air horizontally across the sorbent filters 1,800–2,500 kWh of thermal energy (at 100°C) and 350–450 kWh of electrical energy per ton of CO_2
Chemical reaction	Amine supported on solid porous granules arranged in a proprietary filter
Chemical agent regenerator	Combined temperature and pressure-swing process
CO_2 STREAM	Enrichment of a greenhouse with CO_2, sequester it or production of renewable methane (STORE&GO project)



Pros	Cons
• The pilot plant in Switzerland suggests a good cost forecast thanks to free waste heat.	• High energy consumption

Key features estimates

Cost ($ per t-CO_2)	**$600** **The firm announces less than $100 at large scale.**	🟥
Potential (Gt-CO_2 per year)	**900**	
Water Consumption (km^3 per Gt-CO_2)	**0**	🟩
Risk of reversal	**Dependent on storage**	🟨
Thermal Energy (GJ per t-CO_2)	**6.5–9**	🟥
Electrical Energy (MWh per t-CO_2)	**350–450**	🟥
Land use (m² per t-CO_2 per year)	**2**	🟩

Advantage 🟩 🟨 🟥 **Drawback**

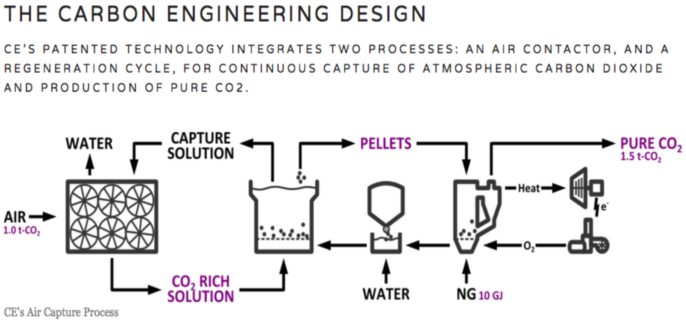
Note: Land use value is based on the requirement of 15800 km² for removing 8 GtCO_2/year (climeworks.com/co$_2$-removal)
Sources: Climeworks, ICEF2018 Roadmap: Direct Air Capture of Carbon Dioxide; A.T. Kearney Energy Transition Institute analysis

DAC with active collector–liquid solvent –temperature swing adsorption: Fact Card

Carbon Engineering (Calgary, Canada)

Collector	Set of fans designed to allow the sorbent to flow downward with gravity while air is blown across it at right angles
Chemical reaction	Aqueous solution of potassium hydroxide (KOH) with calcium caustic recovery cycle
Chemical agent regenerator	High-temperature calcination regeneration process
CO_2 STREAM	Fuel synthesis

Pros	**Cons**
• Liquid sorbent allows the system to work a steady state.	• Needs energy to heat and to create air flow • Needs water



THE CARBON ENGINEERING DESIGN

CE'S PATENTED TECHNOLOGY INTEGRATES TWO PROCESSES: AN AIR CONTACTOR, AND A REGENERATION CYCLE, FOR CONTINUOUS CAPTURE OF ATMOSPHERIC CARBON DIOXIDE AND PRODUCTION OF PURE CO2.

CE's Air Capture Process

Key features estimates

Cost (\$ per t-CO_2)	**\$94 – \$232[1]**	🟨
Potential of pilot plant (t-CO_2 per year)	**370**	
Water consumption (m^3 per t-CO_2)	**4.5**	🟨
Risk of reversal	**Dependent on storage**	🟨
Thermal energy (GJ per t-CO_2)	**5.25 – 8.81**	🟥
Electrical energy (kWh per t-CO_2)	**0 – 366**	🟥
Land use (m^2 per t-CO_2 per year)	**7**	🟩

Advantage 🟩 🟨 🟥 **Drawback**

1. Depending on the ranges for thermal and electrical energies and considering a weighted average cost of capital of 8%
2. Land use value comes from the need of 7000 km^2 for removing 1GtCO_2/year (youtube.com/watch?time_continue=442&v=VtOhPEU8CrA)

Sources: D. Keith et al., "A Process for Capturing CO_2 from the Atmosphere," Joule (June 2018) at p. 1,573-1,594; A.T. Kearney Energy Transition Institute analysis

DAC with active collector–solid sorbent–temperature-swing adsorption: Fact Card

Global Thermostat (Manhattan, New York, USA)

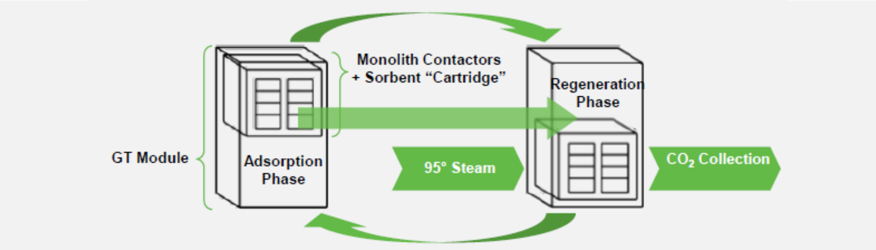
Collector	Set of fans that move air horizontally across the sorbent filters thanks to porous honeycomb ceramic monoliths
Chemical reaction	Amine supported on a porous ceramic “monolith” structure
Chemical agent regenerator	Temperature-vacuum swing process
CO_2 STREAM	Food and beverage company and bio-degradable plastics

Pros

- Cheap manufacturing (mass-produced standard materials)
- Energy efficient

Cons

- Promising but still in development
- Land use (compared with other DAC)



Key features estimates

Cost ($ per t-CO_2)	**$150 company claim for future pilot plant** **$50 (large-scale expectation)**	🟨
Potential of pilot plant (t-CO_2 per year)	**1,000–4,000**	
Water consumption (m^3 per t-CO_2)	**N/A**	
Risk of reversal	**Dependent on storage**	🟨
Thermal energy (GJ per t-CO_2)	**4.4**	🟥
Electrical energy (kWh per t-CO_2)	**160**	🟥
Land use (m^2 per t-CO_2 per year)	**N/A**	🟩

Advantage 🟩 🟨 🟥 **Drawback**

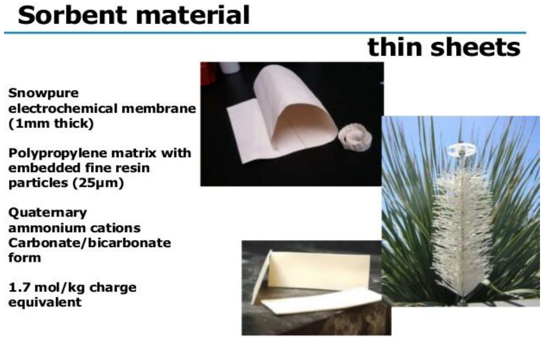
Sources: Global Thermostat, ICEF2018 Roadmap: Direct Air Capture of Carbon Dioxide; A.T. Kearney Energy Transition Institute analysis

DAC with passive collector–solid sorbent–moisture-swing adsorption: Fact Card

Center for Negative Carbon Emission (Tempe, Arizona, USA)

Collector	Passive system that exploits natural wind to move air across the sorbent
Chemical reaction	Anionic exchange resin
Chemical agent regenerator	Moisture-swing process
CO_2 STREAM	Only theorical: storage, materials, EOR

Pros	**Cons**
- Very low energy requirement - Reduced cost	- No partnership with for-profit firm - Only low concentration (5%) CO_2 produced, not compressed - High water consumption



Key features estimates		
Cost (\$ per t-CO_2)	**\$200 down to \$30 (Klaus Lackner claim)**	🟨
Potential of pilot plant (t-CO_2 per year)	**N/A**	
Water consumption (m^3 per t-CO_2)	**5–15**	🟥
Risk of reversal	**Dependent on storage**	🟨
Thermal energy (GJ per t-CO_2)	**1.1**	🟩
Electrical energy (kWh per t-CO_2)	**0**	🟩
Land use (m^2 per t-CO_2 per year)	**N/A**	

Advantage 🟩 🟨 🟥 **Drawback**

Sources: cnce.engineering.asu.edu, ICEF2018 Roadmap: Direct Air Capture of Carbon Dioxide, Y. Ishimoto et al, “Putting Costs of Direct Air Capture in Context,” FCEA Working Paper (2017), T. Wang et al., “Moisture-swing sorption for carbon dioxide capture from ambient air: a thermodynamic analysis,” Physical Chemistry Chemical Physics (2013); A.T. Kearney Energy Transition Institute analysis

DAC with passive collector–solid sorbent–moisture-swing adsorption: Fact Card

Infinitree (New York, USA)

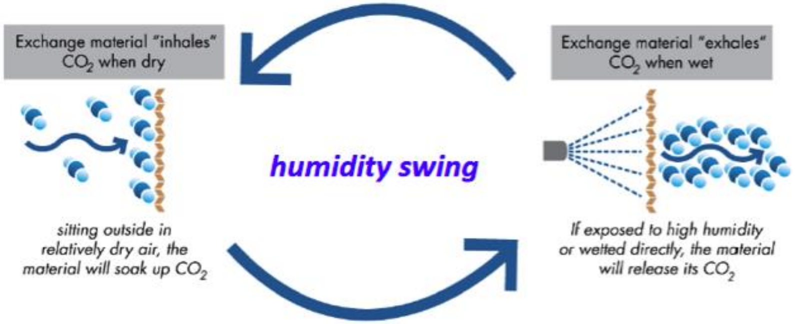
Collector	Passive system that exploits natural wind to move air across the sorbent
Chemical reaction	Anionic exchange resin
Chemical agent regenerator	Moisture-swing process
CO_2 STREAM	Commercial greenhouses

Pros

- Very low energy requirement (does not require combustion)
- Reduced cost
- Steady stream source

Cons

- No operational plant yet
- High water consumption



Key features estimates

Cost (\$ per t-CO_2)	**Low cost**	🟩
Potential of pilot plant (t-CO_2 per year)	**Non-existent**	
Water consumption (m^3 per t-CO_2)	**N/A (high)**	🟥
Risk of reversal	**Dependent on storage**	🟨
Thermal energy (GJ per t-CO_2)	**N/A**	
Electrical energy (kWh per t-CO_2)	**N/A**	
Land use (m^2 per t-CO_2 per year)	**Poor**	🟩

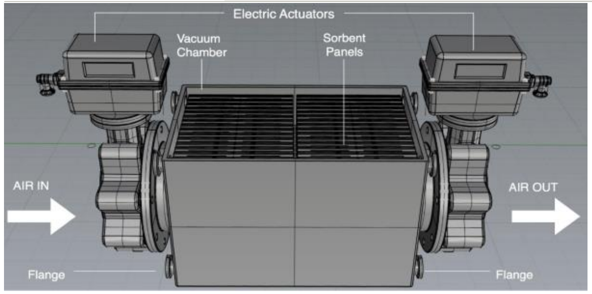
Advantage 🟩 🟨 🟥 **Drawback**

Sources: www.infinitreellc.com; A.T. Kearney Energy Transition Institute analysis

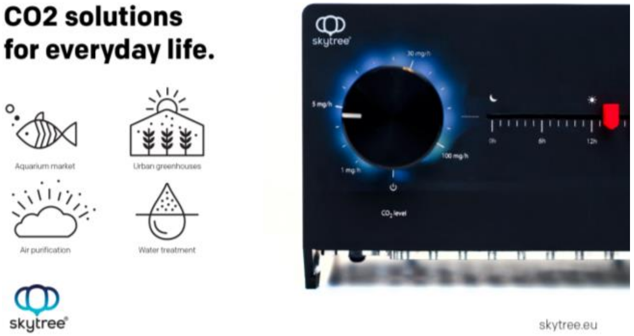
DAC with active collector–solid sorbent–temperature-swing adsorption: Fact Card

Skytree (Amsterdam, Netherlands)

Collector	Active vacuum
Chemical reaction	Solid sorbent
Chemical agent regenerator	Temperature-swing process
CO_2 STREAM	Increasing indoor air quality, boosting agriculture, and transforming CO_2 into methanol



Pros	**Cons**
• Innovative project to turn CO_2 into methanol • Process based on ESA advanced closed loop system	• Small quantity of carbon • High cost



Key features estimates		
Cost ($ per t-CO_2)	**N/A** (high)	🟥
Potential of pilot plant (t-CO_2 per year)	**N/A**	
Water consumption (m^3 per t-CO_2)	**N/A**	
Risk of reversal	**N/A**	
Thermal energy (GJ per t-CO_2)	**N/A**	
Electrical energy (kWh per t-CO_2)	**N/A**	
Land use (m^2 per t-CO_2 per year)	**N/A**	

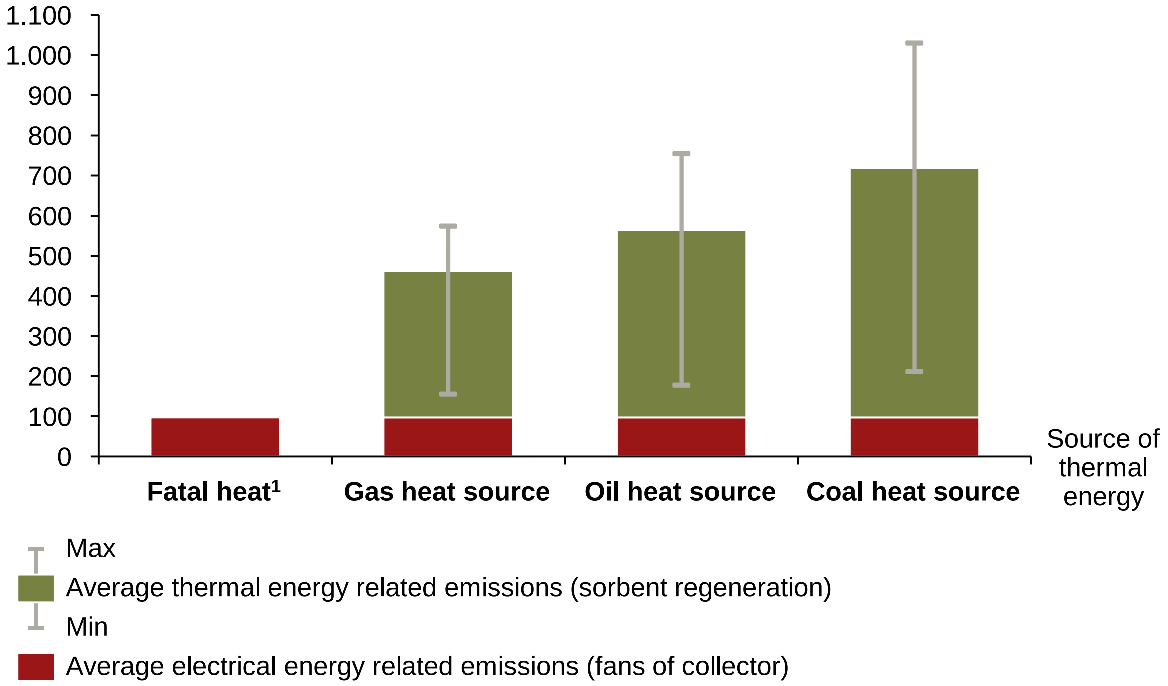
Advantage 🟩 🟨 🟥 **Drawback**

Sources: www.skytree.eu; A.T. Kearney Energy Transition Institute analysis

DAC’s outcome depends on the source of the thermal energy required, as it can be responsible for significant GHG emissions

CO_2 emission from removing one ton of CO_2 in the USA

(kg-$CO_{2emitted}$ /t-$CO_{2captured}$)



- For its power plant in Hinwil, Climeworks harnesses **thermal energy from waste** incineration and processing plant (fatal heat), achieving net negative carbon emission
- In some cases where coal is used as thermal energy source, the **carbon balance** can even be reversed (more than one ton of CO_2 emitted per ton of CO_2 captured)
- Air capture is capital-intensive, forcing every DAC facility to **operate full-time**, so an intermittent non-carbon energy source like solar electric power or wind would be poorly matched to DAC, unless energy storage systems were included to produce baseload power
- A partial exception has been proposed with the CNCE solution where the energy to move the air through the contactor would be provided by the wind

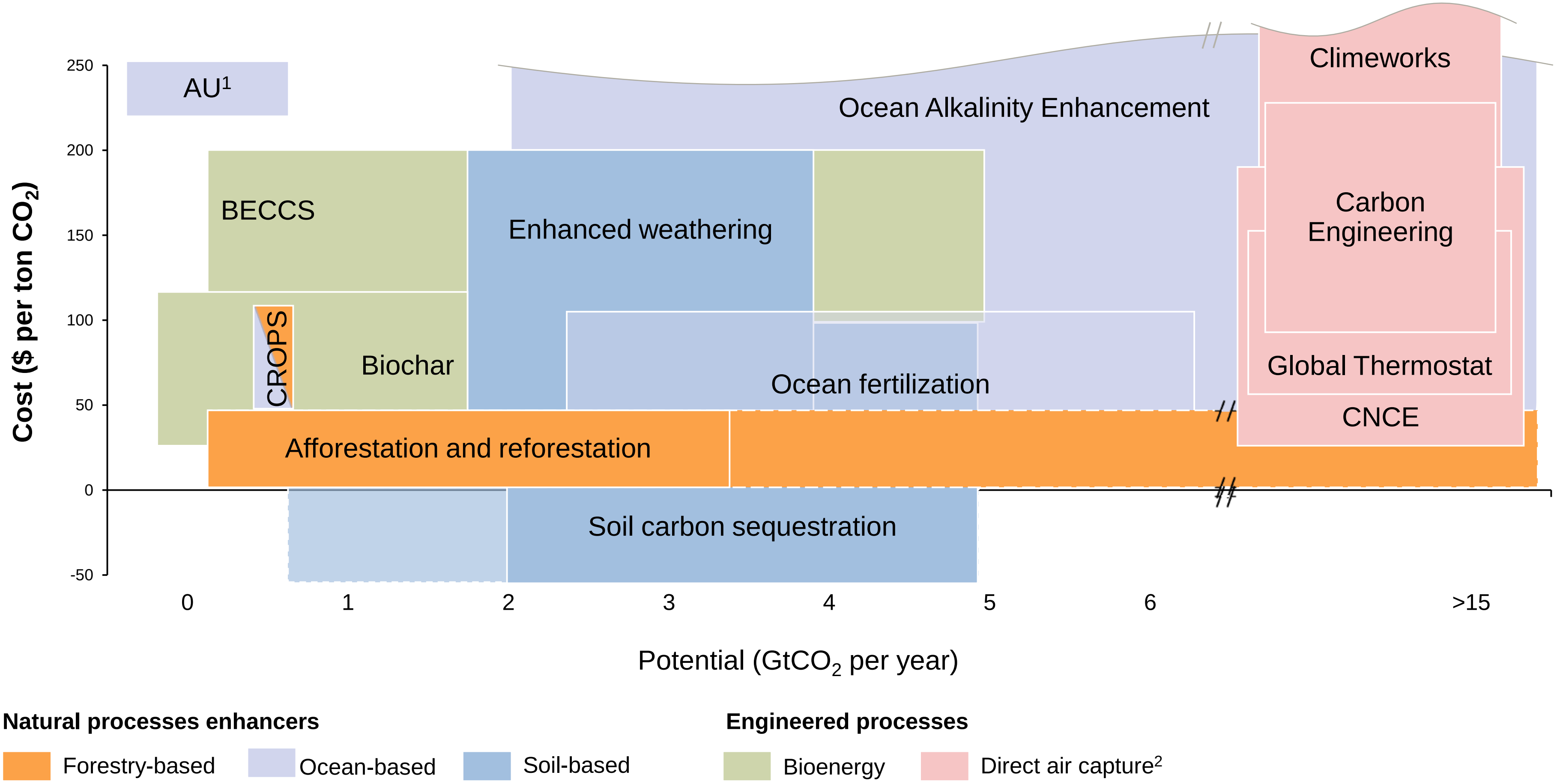
- The CO_2 emissions are based on the values of energy requirement provided in the previous Fact Cards
- We took a value of 0.52 $kgCO_2/kWh$ for the CO_2 emissions related to electrical energy in the USA (EIA)
- We took values of 53, 73 and 104 $kgCO_2/GJ$ for the CO_2 emissions related to gas, fuel and coal use as thermal energy sources (EIA)

[1] Waste heat from a production site, as thermal energy from waste incineration and processing plant (Climeworks, Hinwil), carbon neutral

Source: US Energy Information Administration; Bilan GES ADEME; A.T Kearney Energy Transition Institute Analysis

Large ranges for cost and potential bring big uncertainties about future technologies

Negative emission technologies ranges for cost and potential



1. Cost for artificial upwelling (AU) is not available. 2. Costs for direct air capture technologies are based on projections by each firm for future large scale projects.

Source: IPCC “SR5 – chapter 3” (2018); UNEP (2017); Smith et al (2015); Griscom et al (2017); University of Michigan; E. Strand et al (2009); G. Keil et al (2010); Oschlies, A. et al (2010); Bauman, S.J. et al (2014); Direct air capture companies’ claims

DAC options are constrained by cost, land use, and, above all, energy consumption

Main technical features of promising DAC technologies

	Cost ($ per t-CO_2)	**Potential of pilot plan** (t-CO_2 per year)	**Water consumption** (m3 per t-CO_2)	**Risk of reversal**	**Thermal energy** (GJ per t-CO_2)	**Electrical energy** (kWh per t-CO_2)	**Land use** (m^2 per t-CO_2 per year)	**Verifiability**
DAC Climeworks	🟥 $600 (Less than $100 announced at large scale)	900	🟩 0	🟨 Dependent on storage	🟥 6.5–9.0	🟥 350–450	🟩 2	🟩 Yes
DAC Carbon Engineering	🟨 $94–$232	370	🟨 4.5	🟨 Dependent on storage	🟥 5.25–8.81	🟥 0–366	🟩 7	🟩 Yes
DAC Global Thermostat	🟨 $150 for pilot plant ($50 claimed at large scale)	1,000–4,000	🟨 N/A	🟨 Dependent on storage	🟥 4.4	🟥 160	🟩 N/A	🟩 Yes
DAC CNCE	🟨 Klaus Lackner claim: $200 (and less than $30 at large scale)	N/A	🟥 5–15	🟨 Dependent on storage	🟩 1.1	🟩 0	🟩 N/A	🟩 Yes
DAC Infinitree	🟩 Low cost	Non existent	🟥 N/A (high)	🟨 Dependent on storage	🟨 N/A	🟨 N/A	🟩 Poor	🟩 Yes
DAC Skytree	🟥 N/A (high)	N/A	🟨 N/A	🟨 N/A	🟨 N/A	🟨 N/A	🟩 N/A	🟩 Yes

Advantage 🟩 🟨 🟥 **Drawback**

Source: available in each FactCard; ICEF Roadmap 2018 “Direct Air Capture of Carbon Dioxide” (Dec. 2018); A.T. Kearney Energy Transition Institute analysis

Other negative emission technologies are constrained by their cost, land use and water consumption characteristics

Main technical features of other negative emission technologies

	Cost ($ per t-CO_2)	**Potential** (Gt-CO_2 per year)	**Water consumption** (m3 per t-CO_2)	**Risk of reversal**	**Thermal energy** (GJ per t-CO_2)	**Electrical energy** (kWh per t-CO_2)	**Land use** (m² per t-CO_2 per year)	**Verifiability**
Afforestation and reforestation	5–50	0.5–3.6[1]	92	Yes	0	0	800	Yes
CROPS	50–94	0.7–1	0	To study	Transport	0	0	Yes
Ocean fertilization	23–111	2.6–6.2	0	To study	Mining and transport	0	0	To study
Artificial upwelling	N/a (high)	0–0.9	0	Yes	0-N/A	0-N/A	0	To study
Ocean alkalinity enhancement	10-600	2-20	0	To study	3.2-5.9	~119	0	To study
Enhanced weathering	50–200	2–4	0.4	No	Transport and grinding	N/A	30	Yes
Soil carbon sequestration	-45–100	2.3–5[2]	0	Yes	0	0	0	No
Biochar	30–120	0.3–2	0 (for pyrolysis)	To study	<0	0	160–1,000	Yes
BECCS	100–200	0.5–5	60	Dependent on storage	<0	<0	310–580	Yes

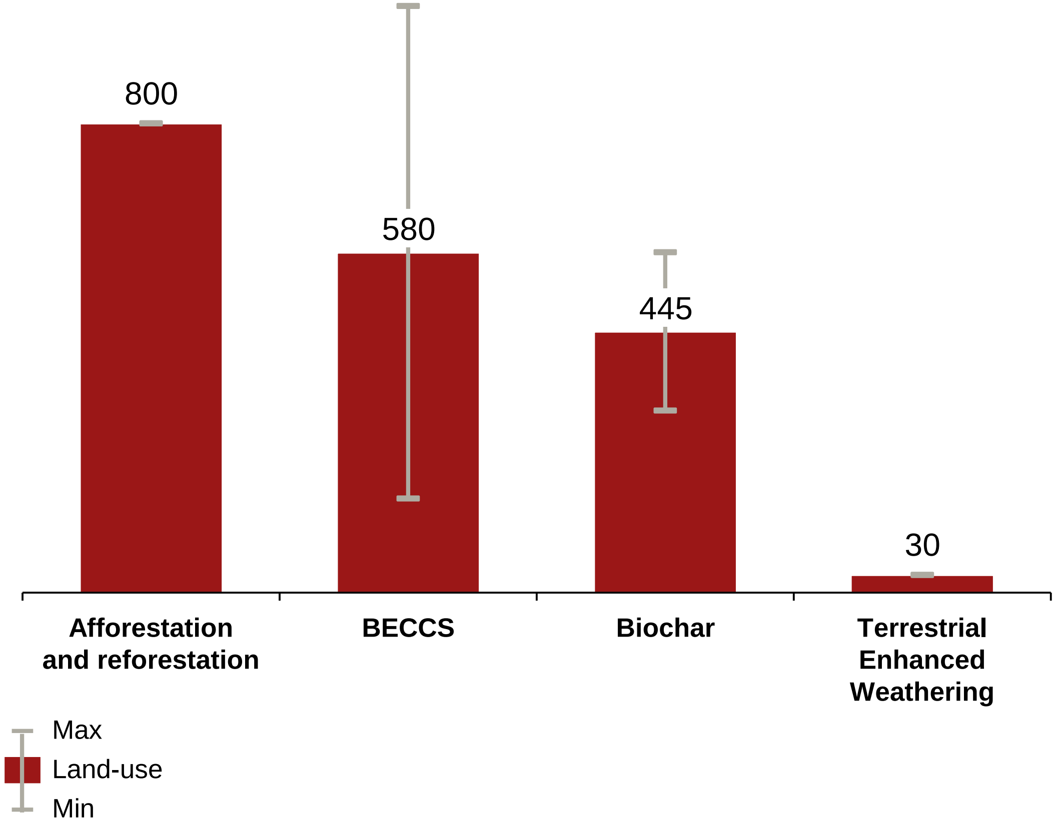
Advantage 🟩 🟨 🟥 **Drawback**

(1) Higher values have been suggested (2) According to UNEP (2017), most of the annual estimates for soil carbon sequestration are based on sequestration values calculated over 20 years.
Notes: CROPS is crop residue ocean permanent sequestration; BECCS is bio-energy with carbon capture and storage
Source: available in each FactCard; A.T. Kearney Energy Transition Institute analysis

Afforestation, reforestation, biochar, and BECCS are the biggest consumers of land, putting them in competition with food and energy supply

Land-use of the most land-consuming NETs

(m^2 per t-CO_2 per year)



- Exploiting the maximum potential of the most land consuming technologies (afforestation and reforestation, biochar, BECCS, and EW) will require **487–780Mha**[1] for removing 14.6 Gt CO_2 per year, including the following:
  - **288 Mha** for afforestation and reforestation (3.6 Gt-CO_2 per year)
  - **155–280Mha** for BECCS (5 Gt CO_2 per year)
  - **32–200 Mha** for biochar (2 Gt CO_2 per year)
  - **12 Mha** for terrestrial enhanced weathering (4 Gt CO_2 per year)
- The total area of land is 12,700 Mha. The agricultural land area is 4,800 Mha (2016).
- Exploiting the full potential of afforestation and reforestation, BECCS, and biochar will require an area representing **10–16% of the global agricultural land in 2016.**

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1. 780 Mha corresponds to 7,800,000 km^2, an area slightly bigger than Australia

Sources: World Bank (2016), data.worldbank.org/indicator/AG.LND.FRST.ZS; A.T. Kearney Energy Transition Institute analysis

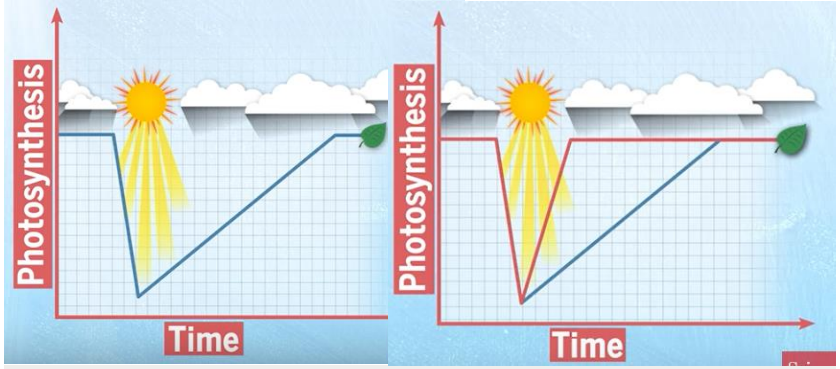
Photosynthesis could be enhanced by genetically modifying plants, reducing land use of afforestation and reforestation, biochar and BECCS

C3[1] photosynthesis efficiency could be increased by using C4[2] genes

- The goal is to **genetically engineer plants and algae** to **improve photosynthesis** efficiency. In this way, those organisms can metabolize more CO_2.
- There are different metabolic pathways for carbon fixation in photosynthesis. The main aim of researches about enhanced photosynthesis is to genetically transform plants with **C3 carbon fixation** in **C4 carbon fixation**, which is more efficient.
- Increasing food production is the first target of investors, but it could be a benefit as well to carbon capture.
- The **C4 Rice Project**, financed by the Bill and Melinda Gates Foundation, aims to improve photosynthetic efficiency by 50% and double water use efficiency by introducing C4 genes in rice plants. The results are a **decrease in fertilizers** use and **less supply of water.**
- The **3to4** project, which raised €6.6 million, is a European organization of researchers to introduce the characteristics of C4 into C3 crops. Some of them are part of the C4 Rice Project. The final objective is to extend this method to other crops, such as wheat or rice.

Accelerated response has improved productivity by 15% on tobacco plants

When a plant detects too much light, it limits photosynthesis. Recovering from this limitation takes various amounts of time.



- Crop leaves in full sunlight dissipate damaging excess absorbed light energy as heat. When sunlit leaves are shaded by clouds or other leaves, this protective dissipation continues for many minutes and reduces photosynthesis.
- An **accelerated response to luminosity** change results in increasing leaf carbon and plant dry matter productivity by **15%** in tobacco plants.

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1. C3, C4 and CAM carbon fixation are the three photosynthetic processes of plants. C3 is the most common (95% of Earth's plant biomass including important food crops such as rice, wheat, soybeans and barley). C3 plants tend to thrive in areas with moderate sunlight intensity, moderate temperatures, high CO_2 concentrations and plentiful groundwaters.
2. C4 fixation is an elaboration of C3 and is believed to have evolved more recently. C4 is the first step in extracting carbon from carbon dioxide to be able to use it in sugar and other biomolecules. C4 plants are able to more efficiently fix carbon in drought, high temperatures, and limitations of nitrogen or CO_2.

Sources: Kromdijk J. et al., Science (November 2016); www.3to4.org; www.c4rice.com; A.T. Kearney Energy Transition Institute analysis

The underlying physical features of technologies determine their advantages and drawbacks

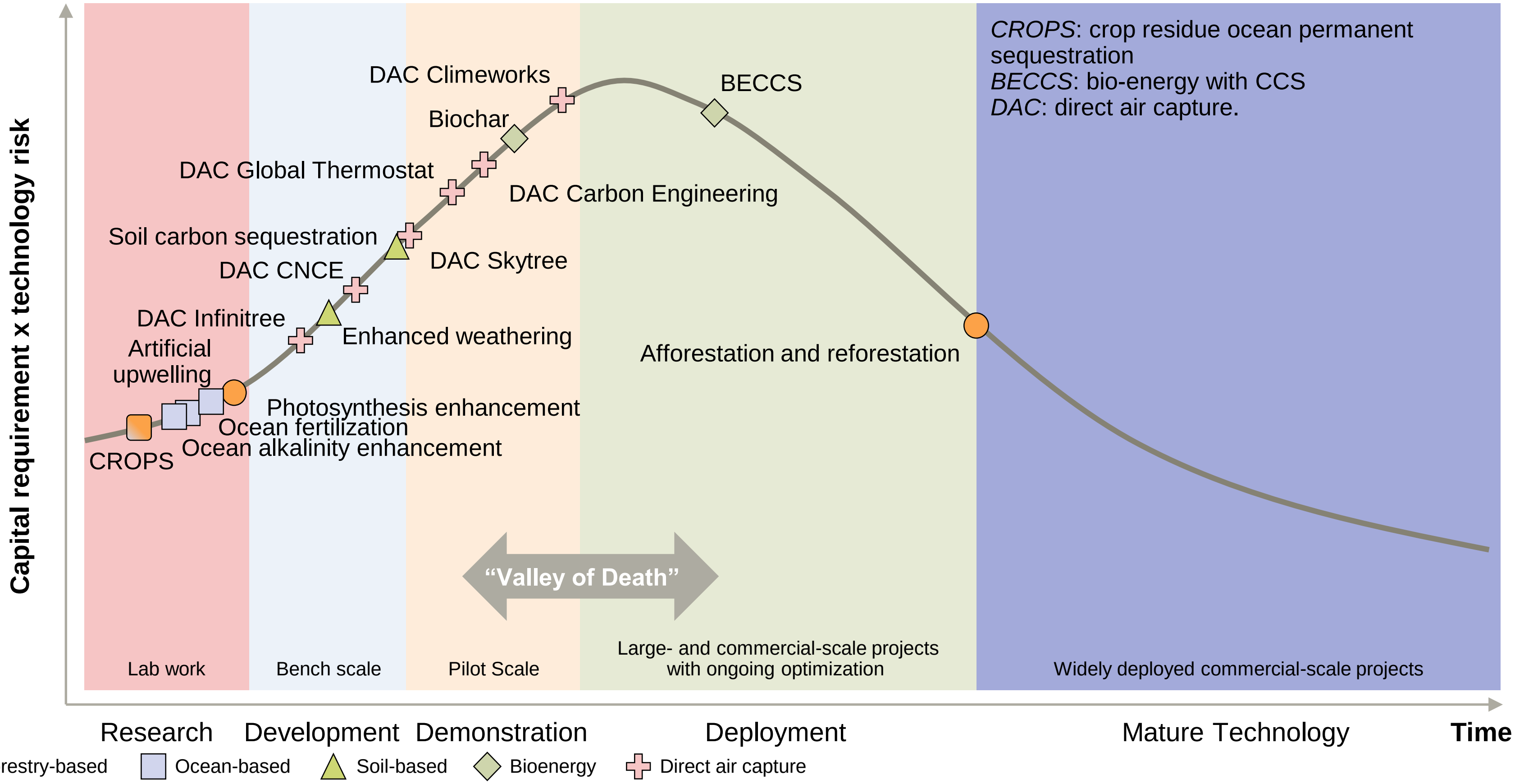
Pros and cons of selected negative emission technologies

	Low cost	High potential	No land, energy, and water competition	Soil nutrient enhancement	Produces energy	Mature technology	High cost	Low potential	Land, energy, or water competition	Risk of reversal	Change in natural cycles	Low scientific knowledge	Specific comments
Afforestation and reforestation	✓	✓				✓			✗	✗	✗		• Mature technology • Possible "leakage"
CROPS											✗	✗	• May violate the London Convention of the seas
Ocean fertilization		✓	✓								✗	✗	• May violate the London Convention of the seas
Artificial upwelling			✓				✗			✗	✗	✗	• Oceans' responsibility legal issues
Ocean alkalinity enhancement		✓	✓									✗	• Reduces ocean acidity • Massive mining activity • May violate the London Convention of the seas
Terrestrial enhanced weathering				✓			✗				✗		• Reduces soil acidity • Massive mining activity
Soil carbon sequestration	✓	✓	✓	✓				✗		✗			• Unchanged land-use • Soil saturation
Biochar				✓	✓	✓			✗				• Limited by soil capacity • Soil pH match needed
BECCS					✓	✓	✗		✗				• Mature technology • Efficiency penalty
DAC		✓					✗						• Modular, decentralized • Applicable to indoor use

Notes: CROPS is crop residue ocean permanent sequestration; BECCS is bio-energy with carbon capture and storage; DAC is direct air capture.
Source:available in each FactCard; A.T. Kearney Energy Transition Institute analysis

Most negative emission technologies are still in the lab or pilot stages and are far from reaching maturity

Technology maturity curve



CROPS: crop residue ocean permanent sequestration
BECCS: bio-energy with CCS
DAC: direct air capture.

Notes: At the "deployment stage", technologies have proven manufacturing process that can be further scaled up at commercial scale; at the "maturity stage", technologies are sold and broadly distributed. Investment valley of death refers to two critical stages: the early demonstration stage, in which capital required tends to outstrip the resources of a typical lab and where the high technology risk deters some private-sector investors; and the early deployment stage, in which high investment requirements and further risk-taking are needed to push the project from demonstration to deployment. Afforestation and reforestation have been widely deployed in the past for building ships, houses, and other wood products.

Source: A.T. Kearney Energy Transition Institute analysis

3. Country Targets, Key Players, and Policy Needs

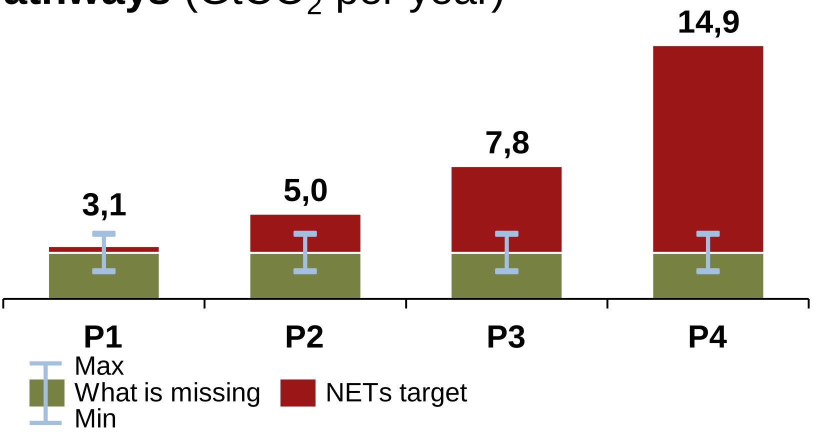
Countries have pledged to net emission reductions, but only afforestation and reforestation are being considered so far

NETs targets included in the UN forestry goals

($GtCO_2$ per year)

1		Forestry-based	1.6–3.8
2		Ocean-based	0
3		Soil-based	~0
4		Bioenergy	~0
5		Direct air capture	~0

Current estimated NETs target and amount missing to meet IPCC proposed pathways ($GtCO_2$ per year)



- In the **COP21**, signatories of the **Paris Agreement** agreed to follow a set of submitted **National Determined Contributions** (NDCs).
- Although countries' NDCs refer to net emission reductions - possibly contemplating NETs - only afforestation and reforestation are mentioned.
- While 74% of the countries include forest-related targets in their NDCs, only 20% of those are quantifiable[1], making global targets hard to access.
- In 2017, the **UN** announced the targets of halting deforestation by 2020 and increase forest area 3% worldwide by 2030, while maintaining or enhancing forest carbon stocks[2]
- With **deforestation** of about **12 Mha** in 2018, and not showing signs of slowing down, halting deforestation by 2020 will be difficult to accomplish. If it continues at current rates, about **300 Mha** will need to be reforested and afforested by 2030 to achieve the target of 3% forest area increase.
- It is estimated that **1.6**[3] **to 3.8**[4] **$GtCO_2$ per year** can be captured in 300 Mha, still insufficient for the IPCC proposed pathways P2, P3, and P4.

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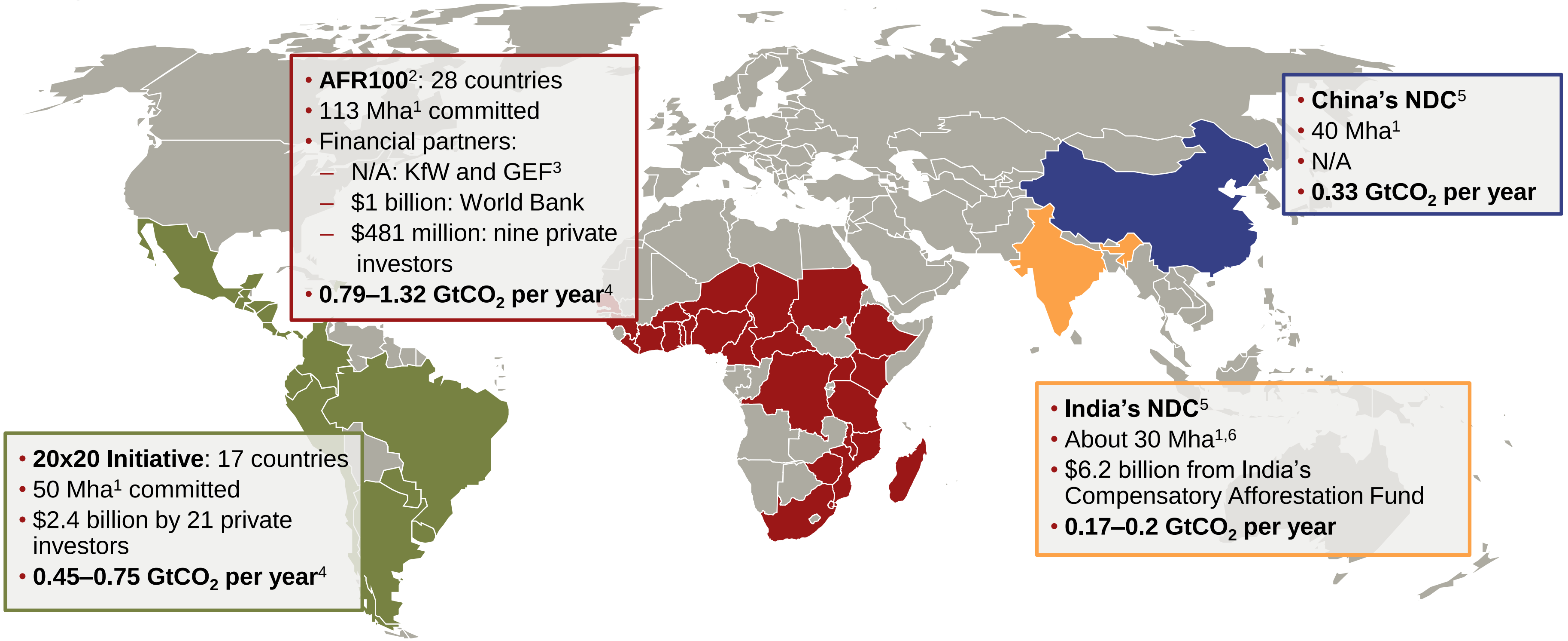
1. As of December 2017, 165 NDCs considered
2. In relation to 2015. 3% corresponds to about 120 Mha additional forest area, the area of Germany, Poland and continental France together
3. Assuming FRA15 statistical profiles and complete forest restoration during the period 2030–2080.
4. According to the IPCC estimate for afforestation and reforestation land use of 800 m² per t-CO_2 per year

Sources: Global Forest Watch; International Union for Conservation of Nature (2017); IPCC (2018) "SR5 – Summary for Policymakers" and "Chapter 2"; Global Carbon Budget 2018; A.T. Kearney Energy Transition Institute analysis

Multi-billion dollar reforestation and afforestation initiatives are expected to capture 1.74 to 2.6 $GtCO_2$ per year, yet realization is still uncertain

Largest announced afforestation and reforestation initiatives



- **AFR100**[2]: 28 countries
- 113 Mha[1] committed
- Financial partners:
  - N/A: KfW and GEF[3]
  - $1 billion: World Bank
  - $481 million: nine private investors
- **0.79–1.32 $GtCO_2$ per year**[4]

- **China's NDC**[5]
- 40 Mha[1]
- N/A
- **0.33 $GtCO_2$ per year**

- **20x20 Initiative**: 17 countries
- 50 Mha[1] committed
- $2.4 billion by 21 private investors
- **0.45–0.75 $GtCO_2$ per year**[4]

- **India's NDC**[5]
- About 30 Mha[1,6]
- $6.2 billion from India's Compensatory Afforestation Fund
- **0.17–0.2 $GtCO_2$ per year**

- Initiatives are also taking place in Colombia, Vietnam, Thailand, Azerbaijan, Haiti, Nepal, Indonesia, and many other countries.
- However, as the forest sector is well known for environmental crime ($50 to $152 Bn per year involved in illegal logging and trade), there are many challenges to the efficacy and transparency of all these programs.

1. 50 Mha corresponds to 500,000 km^2, an area roughly the size of Spain ; 2. African Forest Landscape Restoration Initiative ; 3. Global Environment Facility
4. Assuming FRA15 statistical profiles and complete forest restoration during the period 2030–2060/80. Numbers cross-checked with other approaches.
5. National Determined Contribution. Numbers for $GtCO_2$ per year in this case refer to the period 2016–2030.
6. According to India's NDC of increasing land cover from 24 to 33% and India's Environmental Minister Prakash Javadekar in 2016

Sources: FRA15, Initiative's websites; India's and China's NDCs; Forbes (2016) UNEP-INTERPOL (2016); A.T. Kearney Energy Transition Institute analysis

Other NETs are supported by the public sector, O&G companies and philanthropists, with less investments than in afforestation & reforestation

Few of the biggest carbon dioxide removal projects succeed to raise funds, but it remains complicated

Project		Capital raised	Project type	Investors
Carbon Engineering	🇨🇦	$68,000,000	• Commercialize and enter mainstream markets with its fully demonstrated DAC technology that is able to capture and purify atmospheric CO_2 for under $100 per t-$CO_2$.	• Canada Federal Government, Chevron Technology Ventures, First Round Capital, Lowercase Capital, Occidental Petroleum, BHP Billiton Petroleum, Bill Gates, Peter J Thompson, Oxy Low Carbon Ventures,
Climeworks	🇨🇭	$50,100,000	• The company intends to use the funds to further industrialize its technology and strengthen its market lead within the direct air capture industry.	• Zurich Cantonal Bank, Venture Kick, EIT Climate-KIC
Global Thermostat	🇺🇸	$42,000,000	• Global Thermostat's carbon captures CO_2 from the atmosphere and stores it for reuse (DAC)	• ExxonMobil, Plug and Play Tech Center, NYSERDA, Governor Cuomo
Cool Terra	🇺🇸	$20,300,000	• Provider of high-quality biochar	• Agustín Coppel, North Bridge Venture Partners, NRG Energy, UBS, ConocoPhilips
Illinois Industrial CCS	🇺🇸	$207,000,000	• BECCS for ethanol production led by Archer Daniels Midland	• $141 million from US DOE, matched with more than $66 million private-sector funding from ADM, the University of Illinois, Schlumberger Carbon Services, and Richland Community College

- Silicon Valley investors were generally uninterested in Carbon Engineering’s pitch (although a few did get involved), and few venture capitalists have been willing to join Matt Rogers in backing companies trying to address climate change.
- One of the biggest investors in climate-focused start-ups is **Breakthrough Energy Ventures**, a $1 billion fund that seeks to support the development of world-saving technology that might not have a quick turnaround. This fund is supported, inter alia, by Bill Gates, Jeff Bezos, Marc Benioff, Richard Branson, Jack Ma, George Soros, Meg Whitman, and Mark Zuckerberg.

> *“Money from major philanthropists would not be enough to get even one start-up up to speed, much less the dozens needed to meet the carbon-reduction goals set by international bodies like the IPCC.”*
>
> Matt Rogers, Nest co-founder

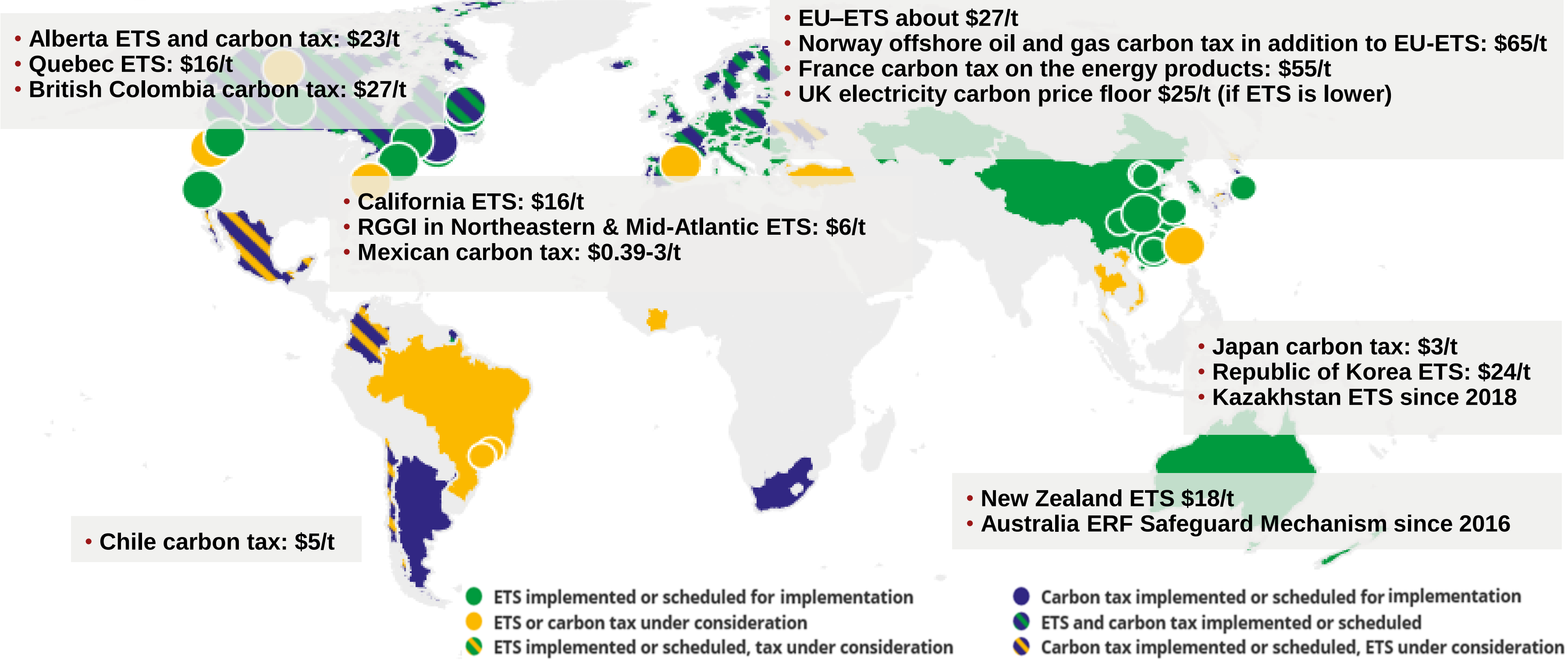
> *“My fund had not made investment in the sector, and I will not see a way for the industry to take off without government policy encouraging it”*
>
> Daniel Oros, partner at G2VP

Sources: The New York Times, 2019, Popper, N.; Financial Times, 2019; i3connect.com; map.geoengineeringmonitor.org; crunchbase.com; pitchbook.com; US DoE; bioenergyinternational.com; A.T. Kearney Energy Transition Institute analysis

Although carbon prices could be a solution, they are generally too low to justify the use of NETs

Explicit carbon price (cap-and-trade or carbon tax)

$ per tCO_2 as of Q2 2019



- **Alberta ETS and carbon tax: $23/t**
- **Quebec ETS: $16/t**
- **British Colombia carbon tax: $27/t**

- **EU–ETS about $27/t**
- **Norway offshore oil and gas carbon tax in addition to EU-ETS: $65/t**
- **France carbon tax on the energy products: $55/t**
- **UK electricity carbon price floor $25/t (if ETS is lower)**

- **California ETS: $16/t**
- **RGGI in Northeastern & Mid-Atlantic ETS: $6/t**
- **Mexican carbon tax: $0.39-3/t**

- **Japan carbon tax: $3/t**
- **Republic of Korea ETS: $24/t**
- **Kazakhstan ETS since 2018**

- **New Zealand ETS $18/t**
- **Australia ERF Safeguard Mechanism since 2016**

- **Chile carbon tax: $5/t**

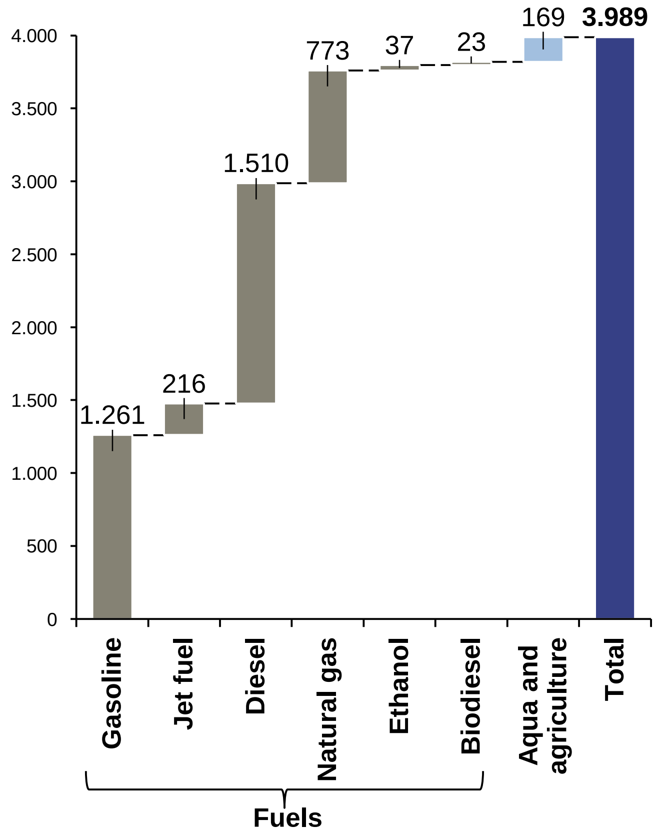
- Although there are carbon markets, some of them do not contemplate NETs (for example, EU ETS for afforestation and reforestation[1]).
- Emission reduction targets are met with carbon pricing, different than forestry targets, met by subsidies and investments.
- Even if included in the trading schemes, carbon prices worldwide are generally too low to justify the commercial use of NETs.

[1] Afforestation and reforestation projects are not allowed to be used as international credits from the Clean Developments Mechanism and Joint Implementation.

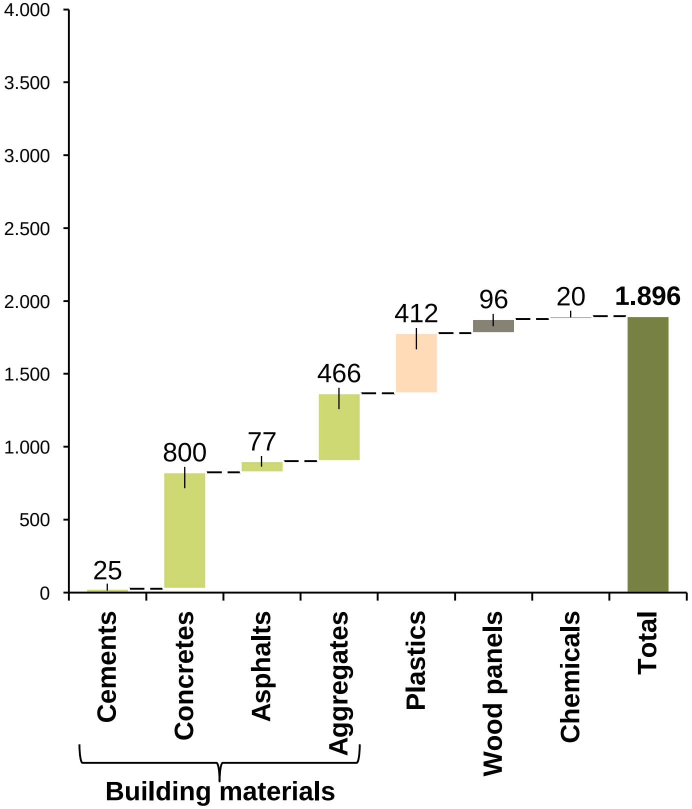
Sources: World Bank (2019), "State and Trends of Carbon Pricing," Carver, T., et al. (2017); A.T. Kearney Energy Transition Institute analysis

Captured CO_2 potentially represents a \$6,000 billion market, mainly by making synthetic fuels and building materials with carbon as feedstock

Market opportunity for zero / low emission solutions ($ billion)



Market opportunity for negative emission solutions ($ billion)



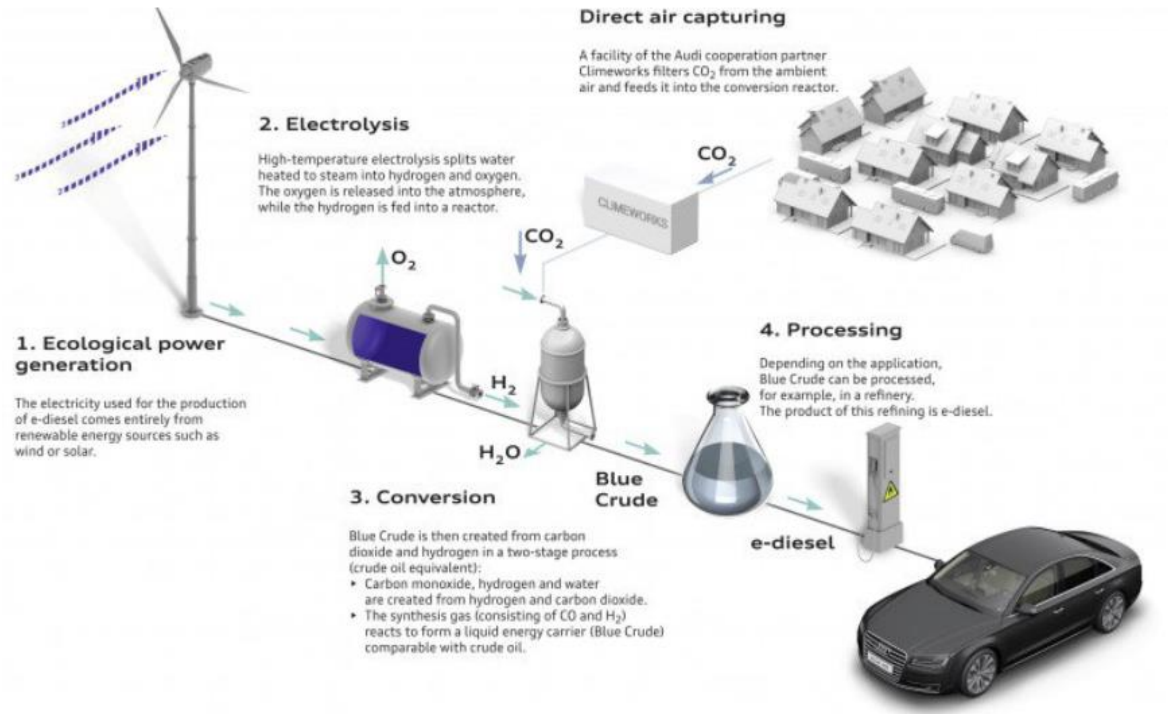
- Conversion of captured CO_2 back into chemicals or hydrocarbon fuels creates a **circular economy.**
- It could lead to a market displacement of traditional fossil fuels, even if it is carbon neutral at best.
- Cement curing and the direct use of synthetic carbonate products as aggregates for construction materials could reduce emissions linked to cement production, one of **the largest emission sources** and potentially make this industry carbon-negative (depending on the production process).

1. Notes: Carbontech is an emerging industrial sector that captures, transports, and converts different forms of “waste carbon” into a diverse array of valued products and services in a climate-beneficial way. The market opportunity is the potential of the market segment, obtained by examining existing technologies and business models for proof of concepts to demonstrate viable feedstocks and conversion processes that could penetrate or disrupt existing market sectors.

Sources: The New Carbon Economy Consortium (2017) A Review of Global and U.S. Total Available Markets for Carbontech; A.T. Kearney Energy Transition Institute analysis

Synthetic fuel made with CO_2 from DAC and green hydrogen[1] could provide a carbon neutral fuel for between €1 and €1.50[2] per liter

Illustration of possible synthetic fuel chain based on DAC and green hydrogen[1]



Direct air capturing

A facility of the Audi cooperation partner Climeworks filters CO_2 from the ambient air and feeds it into the conversion reactor.

2. Electrolysis

High-temperature electrolysis splits water heated to steam into hydrogen and oxygen. The oxygen is released into the atmosphere, while the hydrogen is fed into a reactor.

1. Ecological power generation

The electricity used for the production of e-diesel comes entirely from renewable energy sources such as wind or solar.

4. Processing

Depending on the application, Blue Crude can be processed, for example, in a refinery. The product of this refining is e-diesel.

3. Conversion

Blue Crude is then created from carbon dioxide and hydrogen in a two-stage process (crude oil equivalent):

- Carbon monoxide, hydrogen and water are created from hydrogen and carbon dioxide.
- The synthesis gas (consisting of CO and H_2) reacts to form a liquid energy carrier (Blue Crude) comparable with crude oil.

Expected project characteristics

- One ton of fuel requires **3.2 tons of CO_2** and **294 kilograms of hydrogen**.
- Both Climeworks an Carbon Engineering announce a price of $100 per ton of CO_2 at large scale, and the US government has done a detailed green hydrogen production cost analysis that gives a price from $3.74 to $5.86 per kilogram.
- With these costs, e-diesel could be produced at a cost of $1.42 to $2.04 per liter[3], equivalent to **1.27 to 1.82€ per liter.**
- Powering the plant with **only energy intermittent** input remains a big issue.
- Going from this small-scale project to **a large-scale** one is not guaranteed.

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1. Green hydrogen: H_2 produced from electrolysis powered by renewable energy ; 2. In partnership with Climeworks and Sunfire, Audi announces they will sell synthetic fuels made with CO_2 for between 1 and 50€ per liter, and has already built an operative pilot plant which pumped out 160 liters each day since 2015
3. A.T. Kearney Energy Transition Institute calculation ; 4. MIT researchers have developed a similar system using carbon capture after a power plant to make fuel. The research was funded by Shell Oil and the King Abdullah University of Science and Technology.

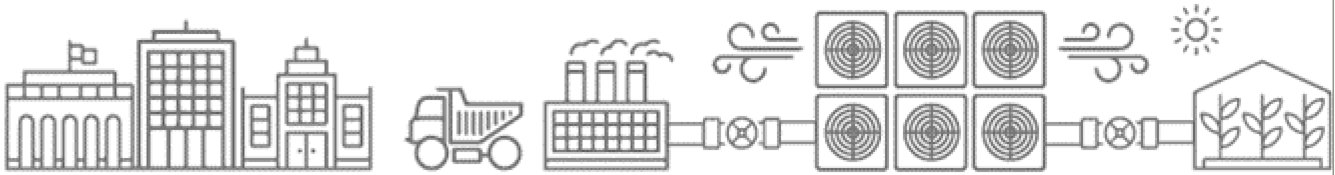
Climeworks also developed a pilot to produce renewable jet fuel from air on the Rotterdam’s Innovation Campus

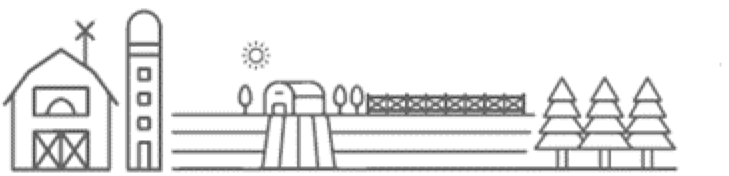
Sources: Audi; www.audi-mediacenter.com/en/press-releases/fuel-of-the-future-research-facility-in-dresden-produces-first-batch-of-audi-e-diesel-352; newatlas.com/carbon-dioxide-fuel-conversion-mit/52367; www.energytrendsinsider.com/2015/04/30/is-audis-carbon-neutral-diesel-a-game-changer; A.T. Kearney Energy Transition Institute analysis

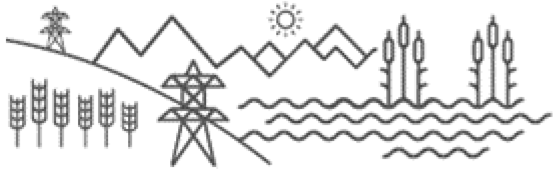
An alliance of universities, national labs, and NGOs working on NET created a consortium to create a new carbon economy

They identify three innovation pathways that hold the most potential to activate the new carbon economy

- **Engineered solutions** are technologies that capture, convert, and store CO_2 from the air and oceans, such as **DAC**, **CCS**, **EW.**
- It also includes **CO_2 conversion to valuable products.**







- **Biological solutions** are the use of working forest and farmland to store carbon, increase yields, and improve ecosystem functions.
- It includes **ecosystem restauration**, **improved forestry practices**, **changes in agricultural practices**, and developing soil amendments that improve soil health.

- **Hybrid solutions** are combining biological and engineered pathways to create energy and/or products.
- It includes **bioenergy with CCS**, **biochar production,** and waste-to-energy systems.

- The alliance objectives a`re as follows:
  - **Close the research gap.**
  - **Share successes and failures.**
  - **Lay the academic groundwork.**
  - **Build the carbon removal network.**

> “We believe human ingenuity and innovation can enable a prosperous, growing economy that captures and stores more carbon than it emits.”

Notes: Launched in 2017, the alliance members are Purdue University, University of British Columbia, Lowrance Livermore National Laboratory, University of Wyoming, National Renewable Energy Laboratory, Colorado State University, Columbia University, Energy Futures Initiative, Cornell University, Colorado School of Mines, Howard University, and Arizona State University.

Sources: Building a New Carbon Economy, the New Carbon Economy Consortium; carbon180.org/newcarboneconomy; A.T. Kearney Energy Transition Institute analysis

The development of a thriving carbon economy has four key success drivers

Success factors for the new carbon economy

		Concrete examples
Global hot spots	• **Industrial clusters** and **regional agricultural areas** with particularly rich opportunities around carbon products or carbon waste disposal • These locations will have a **strong impact** on the development of the new carbon economy.	• **Soil carbon sequestration** requires a combination of the following: – The right biophysical environment (soil type, climate, etc.) – The right economic opportunities and incentives – A community that is willing to change practices
Supply chains	• The new carbon economy will **create new supply chains** for the new products and processes taking advantage of harvested carbon. • **Accurate measurement and verification** of carbon removal, transparency, and traceability will be needed.	• Creating and updating **standards** to drive supply chain innovations • A carbon-neutral and carbon-negative **certification** program that highlights for consumers the climate benefit implicit in the product
Workforce development	• Creation of an **interdisciplinary, entrepreneurial** workforce with an innovation mind-set, flexible to new skills as the new carbon economy takes off, in likely unpredictable ways	• **Key educational topics** include the following: – Simulation, risk assessment, and risk mitigation – Carbon removal monitoring, verification, and accounting – Geology-related analytical tools – Methods to interpret geophysical models for storage – Methods for designing and completing CO_2-related extraction
Data and modeling	• **Transparent data** on the reliability and permanence of the carbon removal and carbon-based products for businesses, policymakers, local and state governments • Data will be used to make decisions about **procurement practices**, **local and regional economic investments**, and the **education and training programs** that must be developed.	• A **carbon economy data hub** would combine non-proprietary experimental and computational data in a searchable infrastructure. • This infrastructure would be built using standardized, open source tools and enable the capture, storage, curation, analysis, and visualization of experimental, computational, demonstration-scale, and pilot-scale results.

Sources: New Carbon Economy Consortium (2017); A.T. Kearney Energy Transition Institute analysis

Four principles for developing NET policy will help unlock the full potential of NETs

Principle	**Support research, development, and demonstration.**	**Support the deployment of short-term opportunities.**	**Integrate NETs into emissions accounting and policy support frameworks.**	**Build system flexibility.**
Motivation	• Reduce scientific uncertainties. • Constrain cost predictions. • Develop new and reliable monitoring methods. • Move incipient technologies further in the maturity curve.	• Start with the low-hanging fruit. • Build skills and experience. • Highlight unforeseen system-level issues.	• Signal to stimulate investments, research, and innovation. • Create an accounting system and carbon pricing framework for NETs, with the ultimate aim of “accreditation and policy parity” with emissions reduction. • Facilitate data compilation, standardization, aggregation, and distribution.	• Develop steps to lay the groundwork for future NETs. • Enable rapid, economically efficient development of future technologies as they appear and become mature. • Avoid lock-out.
Examples	• Develop scientific knowledge, and monitor methods for soil carbon sequestration. • Support the pilots of DAC systems.	• Support soil carbon sequestration practices and biochar through agricultural policies. • Support co-firing BECCS through available subsidy schemes. • Integrate systems with accounting into carbon markets where appropriate.	• Support the accounting system with measurement, reporting, and verification, to track carbon and financial flows along the international value chain.	• Develop capture-ready requirements for BECCS and incentives for fossil CCS to enable conversion to biomass. • Engage early with relevant industries and key stakeholders.

These principles, together with defined targets to be included in the 2020 NDC updates, will build the ground needed for the further development of NETs.

Sources: Lomax, G., et al. (2015); P. Peters, G. and Geden, O. (2017); New Carbon Economy Consortium (2018); A.T. Kearney Energy Transition Institute analysis

Appendix and Bibliography

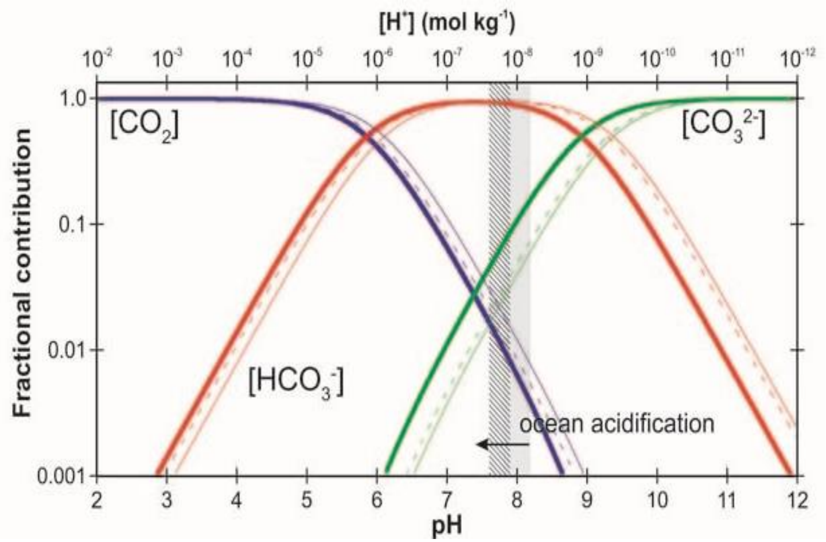
Ocean acidification is threatening marine life, but some negative emission technologies may be part of the solution

Status of Ocean Acidification

- As atmospheric CO_2 dissolves in water, the **pH drops**, making water more and more acidic
- It is estimated that acidity in the oceans has risen **30 percent** over the last 200 years
- Besides causing the **dissolution of the shells** of marine animals, ocean acidification prevents them from developing at their full size and rate
- This happens because shells are made of calcium carbonate **$CaCO_3$**, and to make this component marine creatures combine a calcium ion with carbonate $\boldsymbol{CO_3^{2-}}$
- When CO_2 dissolves in seawater, extra hydrogen ions are produced, which tend to match much better with carbonate ions than calcium ions do, resulting in the formation of bicarbonate ion $\boldsymbol{HCO_3^-}$

$$CO_2(aq) + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^{2-} + 2H^+$$

- Different species are threatened, including **corals** and even **fish**, which have a reduced smell sensitivity, making more difficult to escape predators, ultimately resulting in smaller and fewer fish



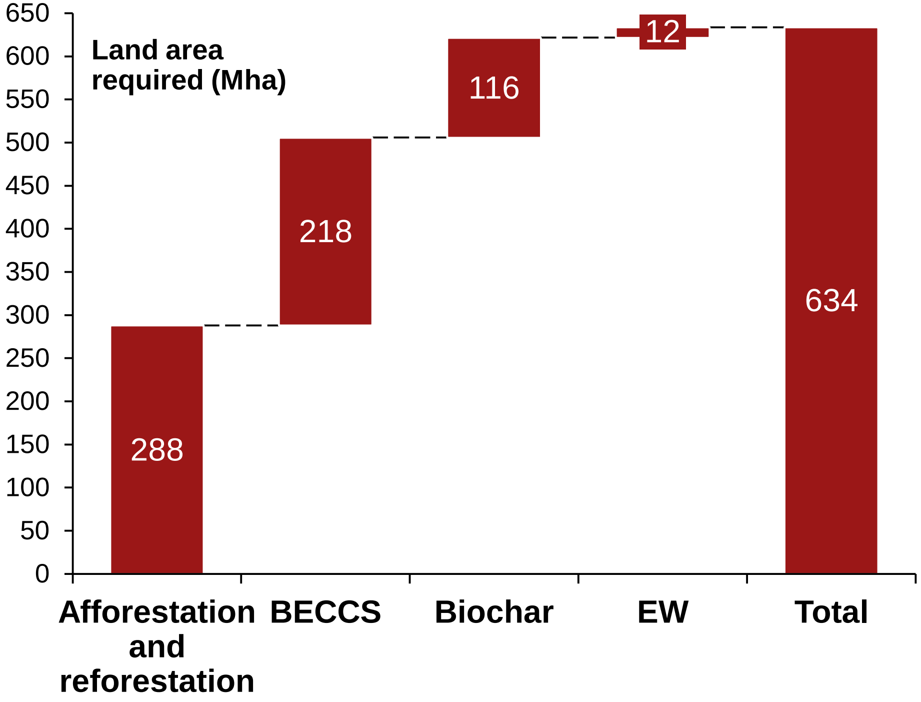
What next?

- Besides drastically reducing carbon emissions, geoengineering solutions will likely be needed
- Among them, ocean alkalinity enhancement and ocean fertilization are expected to both reduce the effects of ocean acidification, and remove CO_2 from the atmosphere

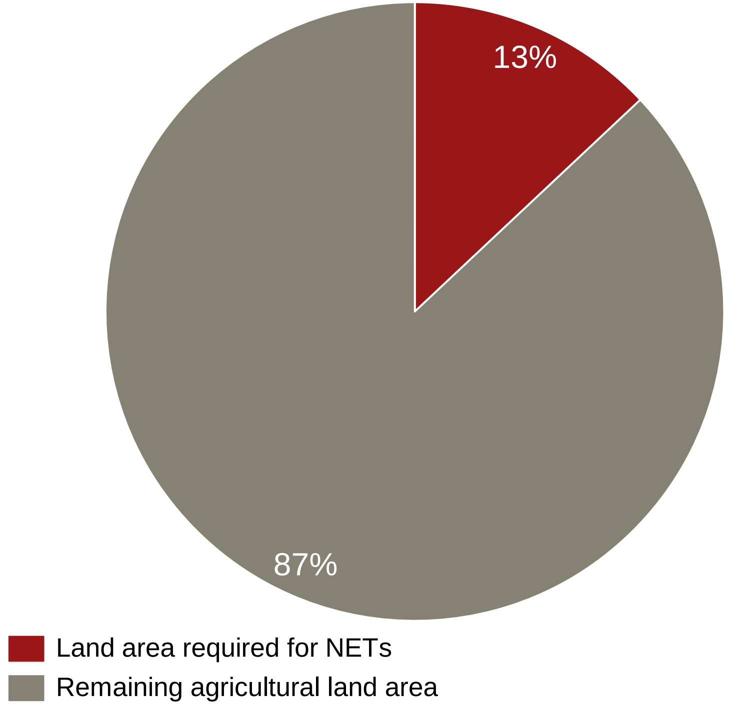
Source: smithsonianmag.com (2018); Feely, R. (2008); Robert, J. (2019); Barker, S. & Ridgwell, A. (2012); A.T. Kearney Energy Transition Institute Analysis

Exploiting the maximum potential of NETs would require 634 Mha of land, representing 13 percent of the total agricultural land area

Land area required to exploit the maximum potential of NET



Share of land required for carbon removal



- The total area of land is 12,700 Mha; the agricultural land area is 4,800 Mha (2016).
- Exploiting the whole potential of afforestation and reforestation, BECCS, biochar, and EW will require **487 to 780 Mha** for removing 14.6 Gt-CO_2 a year, an area representing **10 to 16% of the global agricultural land in 2016.**

Note: Charts built taking the mean value of land use for each NET.
Sources: The World Bank (2016) data.worldbank.org/indicator/AG.LND.FRST.ZS; A.T. Kearney Energy Transition Institute analysis

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