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Carbon” Capture Utilization & Storage (CCUS)

Separating Fact from Fiction

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Content

CO_2 removal (CDR), or “carbon” capture utilization & storage (CCUS), is widely promoted as a critical tool for meeting climate targets. In most “net-zero” pathways, large amounts of future CO_2 removal are assumed to compensate for emissions that cannot be eliminated.

In this blog I examine whether CDR, CCS, CCU, or Direct Air Capture (DAC) actually deliver meaningful “climate benefits” in practice. Using published data from the IEA, IPCC, BCG, and peer-reviewed literature, I illustrate that CCUS **removes very little CO_2, requires large amounts of energy and capital, and delivers no measurable “climate impact” at scale.**

Now before you write my statement off, hear me out… together we will go through what these terms stand for, what the aim/goals seem to be and then we will circle back to my seemingly “harsh” statement above.

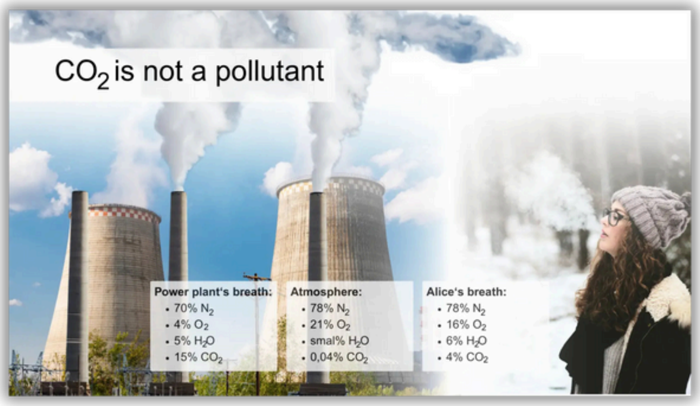
1. Carbon Dioxide Removal, Why?

In its ‘Summary for Policy Makers’ the Intergovernmental Panel on Climate Change (IPCC) has made it clear that “net-zero” emissions need to be realized “as quickly as possible” to mitigate the effects of rising global temperatures. Unlike emissions-reducing “climate solutions”, which limit the amount of CO_2 released into the atmosphere, CO_2 removal (CDR) is defined by the IPCC as ***“activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products.”*** [1]

CCS – “Carbon” Capture and Storage is a misleading term and could more accurately be described as CO_2 Capture and Storage as what is captured is carbon dioxide (CO_2).
Carbon itself is a solid element and a fundamental component of all life on Earth, including about 25% of our bodies, making the idea of “capturing carbon” scientifically inaccurate. However, as the intended meaning is widely understood, the term CCS is generally accepted.

For that reason, I prefer the term **CDR – Carbon Dioxide Removal** over CCS, as it more accurately describes the goal. Direct air capture (DAC) refers to technology aiming to remove CO_2 directly from the air and store it underground permanently.

Figure 1: From Schernikau research and analysis, estimates only for illustration



BCG and McKinsey and many others wrote entire reports on CDR [1,2].

Note: *Interestingly enough, the source of carbon in our bodies originates, practically 100% from atmospheric CO_2. In practice,* ***almost all carbon in living organisms originates from atmospheric CO_2.*** *CO_2 sustains all plant life on Earth, which in turn feeds animals and humans. A portion of the CO_2 humans “capture” is stored in our bodies, while a larger share is exhaled again as CO_2, at a concentration of around 4% compared with the atmospheric average of roughly 0.04%.*

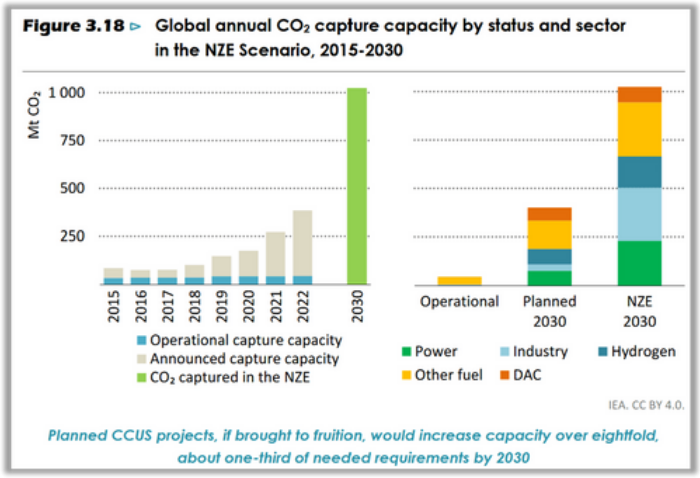
> ***Fact 1: The carbon in your body originates from CO_2. CO_2 is a fundamental building block of all life on Earth, not a pollutant in itself. This is not a matter of belief, but of basic biochemistry.***

CO_2, Life, and the Greenhouse Effect: CO_2 is a trace gas, currently around 420 parts per million in the atmosphere. It is also the primary source of carbon for all living organisms. ***The carbon in plants, animals, and human bodies originates almost entirely from atmospheric CO_2.***

CO_2 is a greenhouse gas, but not a dominant one. ***Water vapour and clouds account for over 90%*** of the greenhouse effect. The warming impact of CO_2 decreases logarithmically, meaning each additional ton has a smaller effect than the previous one. ***A continuous increase in changes in CO_2 concentration therefore translate into smaller and smaller temperature changes.*** (WMO, [3]).

I am of the opinion that our current knowledge and computational methods fall well short of providing reliable predictive capability for the climate system. Whether elevated CO_2 levels are ultimately detrimental to or a benefit for life on Earth is a separate question. My blog does not address the causality between atmospheric CO_2 and these effects. For that discussion, I typically refer readers to Prof. Koonin’s book Unsettled and the writings of Prof Pielke’s writings.

Figure 2: “Net-Zero” pathways assume large CO_2 removal



From IEA Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach – 2023 Update, p132 [4]

Our society, largely driven by regulation, is seeking to remove CO_2 in order to measurably reduce atmospheric concentrations, with the aim of lowering temperatures or limiting future warming, and thereby hoping to reduce future extreme weather and sea-level rise.

Just for reference, there is 100,000 times more carbon per unit of volume in seawater than in air. Oceans are a natural sink of CO_2 as atmospheric concentrations rise for any reason. Over 50% of human emitted CO_2 is taken up by nature, probably close to 30% by oceans alone.

Fact 2: CO_2 is a trace gas that acts as a minor greenhouse gas, with diminishing impact on temperatures

The idea of CO_2 removal exists because “Net-Zero” requires it. Emissions reduction alone do not meet stated targets, so large future volumes of CO_2 removal are assumed. For this reason, direct air capture (DAS) continues to attract investment despite limited practical value.

- The IPCC projects that between 6 and 10 billion tons of CO_2 ($GtCO_2$) would need to be removed annually by 2050 [1] to meet “Paris Agreement” goals
- IEA predicts in its net zero pathway that 6 billion tons of CO_2a. need to be removed by 2050 [4] FYI, IEA’s or anyone “net-zero” is actually not net-zero because CH4 will never reach net-zero and is not modelled to do so”.
- BCG estimates, in a second degree pathway, that 1 billion tons of CO_2 would need to be captured and permanently removed by 2035 [2]
- McKinsey estimates that $6-16 trillion investment in CO_2 removal would be required until 2050 ($0.5-2 trillion until 2030)

2. How do we capture CO_2 & what are storage risks?

It is stated that since 1996, in almost 30 years, less than 400 million tons of CO_2 have been captured and injected underground globally according to the first complete record of global underground CO_2 storage [5].

A substantial share of this CO_2 was used for **enhanced oil recovery (EOR)** rather than permanent storage.

Even among storage projects, not all injected CO_2 remains underground.

Realistically, cumulative ***net removal is likely closer to 100–200 million tons,*** achieved at a cost of tens of billions of dollars (total expenditure for this achievement is estimated somewhere between 60-120 billion USD). The obvious fact is that not all CO_2 was removed from the atmosphere, which caused the “climate impact” to be substantially lower than anticipated.

Global operational ***CCS capacity today (2025) is around 50 million tons per year,*** a negligible fraction of annual global emissions of ~70 billion tons of CO_2e in 2025 (inc. CH4 assuming GWP20).

Climate models and “net-zero” pathways assume billion-tonne-scale CO_2 removal within a decade as actual CCS deployment operates at million-tonne scale after 30 years of effort. ***This gap is not a matter of policy ambition but of physics, energy, and material constraints.***

Capturing CO_2 is only the **first step** in any attempt at “permanent carbon dioxide removal.” In practice, CO_2 capture focuses on sources where CO_2 concentrations are already relatively high, mainly thermal power stations. Typical concentrations are:

- **Coal-fired power plants (conventional combustion):** ***~12–15% CO_2*** in the flue gas
- **Integrated Gasification Combined Cycle (IGCC) plants (without CCS):** ***~6–8% CO_2*** in the exhaust
  - Coal is **gasified, not combusted**
  - **Pre-combustion CO_2 concentrations reach *~30–40%***, which would be ideal for capture
  - If CO_2 is not captured before combustion, this ***high concentration is lost through dilution***
  - **Gas-fired power plants:** ***~3–5% CO_2*** in the exhaust, despite higher overall fuel efficiency
- **Direct Air Capture (DAC) for comparison:** ***~0.04% CO_2*** in ambient air

Fact 3: For a modern coal-fired power plant with ~90% CCS, the all-in primary-energy requirement per delivered MWh is typically ~40% higher than without CCS (see Appendix 1)

This includes additional coal consumption, capture and compression, increased mining, handling and transport of the extra coal, and CO_2 transport and injection for storage, assuming all CO_2 is permanently removed, which in practice is not the case.

Figure 3: “Source Do et al 2022 [9]

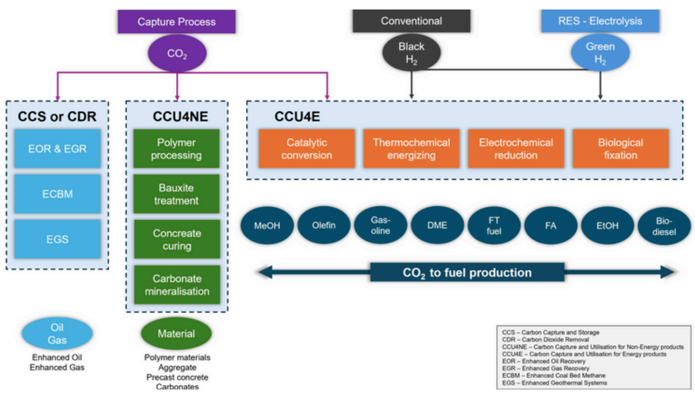
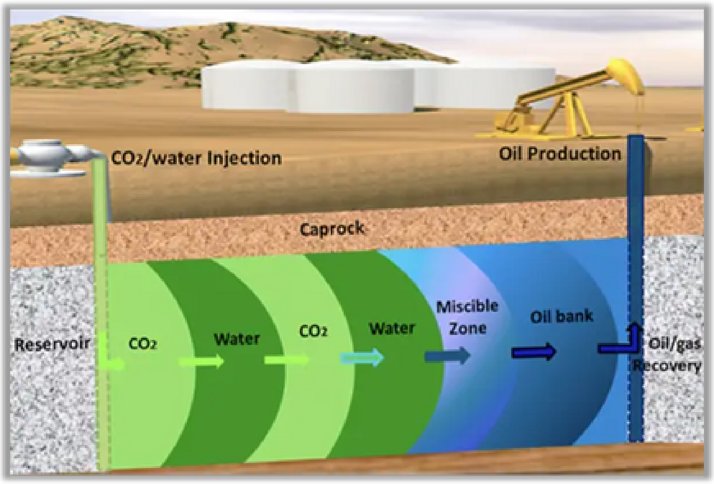


Figure 4: Source: Carbon Industrial Usage – Enhanced Oil Recovery (EOR) [10]



Fact 4: The “energy cost of CCS” for a coal-fired power station is about 1 MWh per 1 ton of CO_2 (see Appendix 1)

Considering the fuel multiplier for gas-fired power plants with CCS, we are looking at about 25% less, because gas-fired power stations tend to be more fuel efficient, despite the smaller CO_2 concentration in the exhaust stream.

CCS does not make energy systems cleaner; it makes them larger, more complex, and less efficient.

According to the International Energy Agency (IEA), Germany plans a CCS capacity of around **2 million tons of CO_2 per year.** At this scale, the contribution is **“climatically negligible”**, illustrating the large gap between policy ambition and reality. [6]

When we look at the sub-optimal results **of Australia’s flagship CCS project (see details on Gorgon in the Appendix below)** and **Germany’s climatically negligible ambitions,** we see that CCS so far delivers neither reliability at scale nor meaningful impact when deployed.

Geological storage also carries risks. Another key challenge in carbon capture and storage (CCS) is the ***long-term management of carbon dioxide after capture.*** The most widely proposed solution is geological storage, injecting CO_2 underground into depleted oil and gas reservoirs (where available near the capture site) or into deep saline aquifers. One of the most prominent examples of the latter is the CO_2 injection system developed as part of the Gorgon LNG Project in Western Australia, operated by a Chevron-led joint venture (with Shell and ExxonMobil as partners).

The Gorgon gas field off the coast of Western Australia ***was approved on condition the CCS project could and would capture 80 per cent of the CO_2 emitted, or 4 million tons a year. What it actually achieved in fiscal 2024 was just 1.6 million tons of CO_2*** equivalent [7].

A further consideration for any subsurface CO_2 storage project is the consequence of unintended CO_2 release. Carbon dioxide is an asphyxiant and, being denser than air, may accumulate near ground level under certain conditions, especially in confined or low-lying areas. ***At sufficiently high concentrations (5% and above, compared to 0.04% ambient CO_2 concentration) CO_2 can cause rapid loss of consciousness and death*** [8].

A natural release of CO_2 from a volcanic crater lake led to the asphyxiation deaths of roughly 1,700 people and thousands of animals in 1986. *See Appendix 1 for more details.*

In our own peer-reviewed research Schernikau/Smith 2022 “Climate Impacts’ of Fossil Fuels in Today’s Energy Systems” we come to the conclusion that, because of the CO2 and CH4 emissions of gas, natural gas is not “better for the climate” than coal. *See Appendix 1 for more details and additional sources.*

3. Utilizing CO_2, and make what?

CCU refers to CO_2 Capture and Utilisation. Please keep in mind that ***using CO_2 to produce fuels or chemicals does not remove it from the atmosphere.*** It means expending additional energy to make other products out of CO_2, usually fuels, that later release the same CO_2 or more.

As with all processes, capturing CO_2 and using the carbon it contains to produce new products makes sense only where it is both economically and energetically viable. Dr Bodo Wolf, a dear friend of mine, wrote a famous book in 2005 *“Öl aus Sonne – Die Brennstoffformel der Erde” or “Oil from Sun, Earth’s fuel formular”*. Wolf, a gasification expert, entrepreneur and inventor, described the logic of reusing the element carbon for fueling our world.

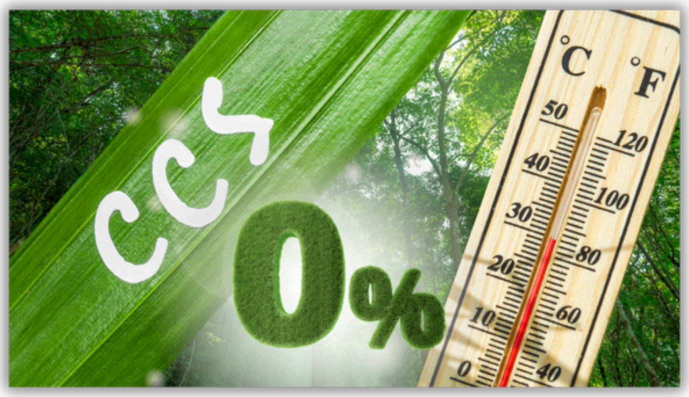
CO_2 is already in its lowest chemical energy state, as fully oxidised carbon. ***Any attempt to “use” CO_2 therefore requires the addition of energy***, usually in large amounts.

- When “making” CO_2 into hydrocarbons or “e-fuels” (methanol, synthetic diesel/jet) one requires a lot of hydrogen, typically from electrolysis. Hydrogen dominates both the energy cost and monetary cost in these routes. See here for details on “green” hydrogen.
- For products such as urea or some carbonates, CO_2 is used as a feedstock and the “energy cost” can be lower

The industrial use of CO_2 can be classified into three main categories:

- CCS or CDR to sequester CO_2 underground or for enhanced oil recovery EOR
- carbon capture and utilization for non-energy products (CCU4NE),
- and for energy products (CCU4E), as show in below graph

Fact 5: CO_2 utilization to produce fuels represents an additional energy sink, and one that is more energy-intensive than CO_2 capture and storage CCS.



Fact 6: Producing fuels from CO_2 using hydrogen carries a total system-level energy cost of 8–10+ MWh per tonne of CO_2, and the CO_2 is ultimately still released into the atmosphere. The "energy cost" for producing and refining oil is significantly lower.

Enhanced Oil Recovery (EOR) is currently the most common use of captured CO_2. It is economically attractive and energy-positive because it produces oil, but its "climate benefit" is questionable.

EOR is a set of techniques used to extract oil that cannot be produced using normal primary or secondary methods. After a natural oil reservoir (pressure and waterflooding) is exhausted, EOR can substantially increase total oil recovery. EOR is usually economically attractive in mature oil fields

- Primary recovery gets ~10% of the oil
- Secondary recovery (water or gas injection) increases this to 20–40%
- EOR can increase recovery to 30–60%+

CO_2-EOR is the most widely used method globally. CO_2 mixes with oil, making it flow more easily. It can store CO_2 underground while producing more oil. But the "climate benefit" is debated because EOR operations are energy-intensive and the produced oil is later burned [11].

Fact 7: Enhanced Oil Recovery it the most common utilization of CO_2, with questionable "climate benefits" if any at all. However it makes economic sense and is energy positive because it produces oil that would otherwise not be recoverable.

4. Direct Air Capture, what logic?

Fact 8: DAC takes on physics, scale, and time simultaneously — and loses this fight against all three. The energy cost of DAC is ~2–4 MWh/ton CO_2.

Direct Air Capture (DAC) faces a fundamental problem: dilution. Atmospheric CO_2 makes up only about 0.04% of the air, meaning DAC systems must process enormous volumes of air to capture very small amounts of CO_2. If you thought carbon capture and storage was expensive, then direct air capture and storage will be far more expensive.

Separating a substance at such low concentrations is inherently energy-intensive. Most of the energy in DAC is spent moving air, not capturing CO_2. While capture from power-plant exhaust is already costly at much higher concentrations, doing so from ambient air multiplies the challenge by orders of magnitude.

If you assume the energy cost to be only ~2–4 MWh/ton CO_2, then 1 billion tons of CO_2 "removal" annually using DAC would be 2,000 to 4,000 TWh p.a. (8-15% of global electricity consumption).

DAC is therefore technically possible but **practically unscalable.** It exists mainly as a modelling assumption that allows "net-zero" scenarios to close mathematically, not as a realistic pathway for large-scale CO_2 removal.

Oh, there is one more "small point" to consider, ***the atmosphere and the surface waters are in dynamic equilibrium, which means that if we were to remove CO_2 from the atmosphere, then CO_2 would be released from the surface water back into the atmosphere.*** By the way, only about 45% of emitted CO_2 becomes – what is referred to as – "airborne", the remainder is taken up by nature, our oceans and the biosphere. [12,13]

"As a general technology against climate change with a practical and significant impact at scale, DAC is completely infeasible." (Prof Rasmussen, Cambridge, [13])

5. The "climate impact" of CO_2 removal

As discussed before, let's assume that 200 million tons of CO_2 have actually been globally cumulatively removed using CCS since 1996… what was the "climate impact"?

The unpopular truth is…even if all CCS to date had permanently removed 200 million tons of CO_2, the climate impact would be effectively zero.

The IPCC offers a simplified **MAGICC online calculator** where you can enter the "avoided" CO_2 emissions in tons and see the impact on the temperatures in 75 years, in 2100. See Appendix 2 for more details on IPCC's MAGICC.

Fact 9: Assuming that, during the past 30 year, CCUS removed about 200 million tons of CO_2 (that never resurfaced) from the atmosphere then, according to IPCCs MAGICC, 2100 temperatures reduced by ≈ 0.0001 °C

- Let's round this up to zero as one cannot measure it, nor will it have any impact at all on extreme weather nor sea-levels

The estimated temperature impact of all historical CO_2 removal rounds to zero: it is not measurable and has no effect on extreme weather or sea-level rise.

As a rule of thumb using the IPCC's MAGICC model, ***1 billion tons of permanent CO_2 removal <u>each year</u> for 75 years*** *and utilizing 8-15% of global electricity doing so would then result in only* ***≈0.035 °C less warming in 2100****, still below detectability.*

- Using the IPCC AR6 model framework, this corresponds to roughly **7 mm of avoided sea-level rise** by 2100, also **not measurable.**
- For context, the IPCC projects that by 2100 global mean sea level would be about **10 cm lower at 1.5 °C warming** than at 2 °C warming, with a wide uncertainty range of **4–16 cm**; these projections remain disputed.

Summary

Let's review the facts…

Fact 1: The carbon in your body was once CO_2. ***CO_2 is a fundamental building block of all life on Earth, not a pollutant in itself.*** This is not a matter of belief, but of basic biochemistry.

Fact 2: CO_2 is a trace gas that acts as a minor greenhouse gas, with diminishing impact on temperatures.

Fact 3: For a modern ***coal-fired power plant*** with ~90% CCS, ***the all-in primary-energy requirement per delivered MWh is typically ~40% higher than without CCS.***

Fact 4: The "energy cost of CCS" for a coal-fired power station is about 1 MWh per 1 ton of CO_2

Fact 5: CO_2 utilization to produce fuels represents an additional energy sink, and one that is more energy-intensive than CCS.

Fact 6: Producing fuels from CO_2 using hydrogen carries a total system-level energy cost of roughly 8–10+ MWh per tonne of CO_2, and the CO_2 is ultimately still released into the atmosphere.

Fact 7: Enhanced Oil Recovery it the most common utilization of CO_2, with questionable "climate benefits" if any at all, it makes economic sense and is energy positive because it produces oil.

Fact 8: DAC takes on physics, scale, and time simultaneously — and loses this fight against all three. The energy cost of DAC is ~2–4 MWh/ton CO_2.

Fact 9: Global CCUS roughly removed 200 mln tons of CO_2during the past 30 years (that never resurfaced) from the atmosphere and according to IPCCs MAGICC reduced 2100 temperatures by ≈ 0.0001 °C

In my humble opinion, considering the facts above, carbon dioxide removal CDR does not eliminate relevant emissions and is on average and at scale, an economic waste creating environmental concerns rather than solving them. It only transfers emissions from the atmosphere into engineered geological systems that must remain stable for centuries or millennia. This creates a long-term liability that requires continuous monitoring, regulation, and institutional stability far beyond typical infrastructure lifetimes. Failure does not need to be frequent to be consequential.

CO_2 removal is only possible by drastically reducing the net energy and raw material efficiency of our existing energy systems **counteracting the intent** of environmental protection. The case of coal where CCS results in about 40% higher coal consumption for the same electricity output is a good illustration. With the increase in fuel consumption, mining activity, water usage and the infrastructure footprint, the resource intensity of ***CO_2 removal directly contradicts the goal of reducing environmental pressure.*** Even if CO_2 were the only concern, CDR worsens other environmental dimensions.

Even if the world could effectively capture and permanently remove 1 billion tons each year, the temperature impacts are hardly measurable. The economic and environmental costs are large, very large… The hundreds of billions to be spent on CDR could instead be used for improving technology, delivering reliable, affordable infrastructure, installing newest filter technology, improving net energy and raw material efficiency, or support education, poverty reduction, and health. We need solutions that deliver immediate and measurable societal benefits.

For more details please refer to our book ***"The Unpopular Truth… about Electricity and the Future of Energy"***

Appendix

Appendix 1: On CO_2 capture in power plants

Capturing and compressing CO_2 as part of Carbon Dioxide Removal (CDR) is **highly energy-intensive.** Even before transport, storage, or utilisation are considered, several system-level penalties apply:

- **Post-combustion CCS at a modern coal-fired power plant**
  - Reduces net plant efficiency by roughly **25–30%** at system level
  - This reduction reflects **capture and compression only**, excluding transport, storage, or utilisation
- **System-level fuel-efficiency loss**
  - A reduction in net efficiency from **2% to 31.4%** corresponds to a **~38% increase in fuel consumption per delivered MWh** US Department of Energy NETL [15]
  - This means substantially more coal must be burned to produce the same amount of electricity
- **Upstream fuel inefficiency**
  - The additional **~38% of coal** must be mined, transported, and processed
  - These upstream activities likely add **another ~1% of primary energy cost**
- **CO_2 transport and storage**
  - Compressing, transporting, and injecting CO_2 underground also requires energy
  - While small compared to capture and compression, this likely adds **another ~1% efficiency loss**

Public reporting indicates persistent underperformance at Gorgon, consistent with **loss of injectivity.** The project joint venture has reported "sand" emerging from pressure-relief boreholes, without clarification as to whether this material is silica or carbonate. Either outcome points to geochemical degradation of the storage formation and illustrates a fundamental risk of saline aquifer CO_2 storage: **the storage medium itself can be damaged by the injected CO_2.**

There are apparently only two success stories in Norway of 13 CCS projects reviewed around the world [7].

The Lake Nyos disaster in Cameroon (1986) illustrates the behavior and lethality of large CO_2 releases: a sudden natural release of CO_2 from a volcanic crater lake led to the asphyxiation deaths of roughly 1,700 people and thousands of animals as the dense gas cloud flowed downslope and displaced oxygen. It provides a relevant physical analogue for CO_2 dispersion and hazard in worst-case release scenarios.

In LNG production, CO_2 is typically removed from raw natural gas to enable liquefaction and transport. The CO_2 content of natural gas varies widely by field and can be high in some developments. Technical literature indicates that in many baseline LNG designs the removed CO_2 may be vented unless capture and storage is added, though comprehensive global disclosure is limited. The vented upstream CO_2 of LNG is not considered when marketed as comparatively "clean" on a combustion-only basis. In our own peer-reviewed research Schernikau/Smith 2022 **"Climate Impacts' of Fossil Fuels in Today's Energy Systems"** we come to the conclusion that, because of the CO2 and CH4 emissions of gas, natural gas is not "better for the climate" than coal.

Appendix 2

The IPCC offers a simplified MAGICC online calculator:

- MAGICC = *Model for the Assessment of Greenhouse-gas Induced Climate Change.*
- It is a reduced-complexity climate model, not a general circulation model (GCM). It is widely used by IPCC, integrated assessment models IAMs, and policymakers because it is fast, transparent, and tunable, not because it resolves clouds or oceans in detail.
- Of course, this assumes that the climate models and scenarios used to calculate are correct, which is by now in widespread serious doubt.
- MAGICC assumes, the climate system behaves approximately like the mean of CMIP5 models, which is a highly biased assumption…. But for the sake of this example, let’s assume MAGICC is correct, see magicc.org

Links and Resources

[1] Carbon Removals: How to Scale a New Gigaton Industry | McKinsey. 2023. (link)

[2] BCG: Boosting Demand for Carbon Dioxide Removal. 2024. (link)

[3] WMO 2021, World Meterological Organization, Greenhouse gases, (link).

[4] IEA Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach – 2023 Update. 2023. (link)

[4a] IEA, Carbon Capture and Storage: What Can We Learn from the Project Track Record? 2024. (link) p6

[5] News, Norwegian SciTech. “First Complete Record of Global Underground CO_2 Storage.” Norwegian SciTech News, November 2025. (link)

[6] IEA: Germany 2025 – Analysis. 2025. (link) p.24

[7] RenewEconomy. “Gorgon AUS: Expensive Failure: Flagship Gorgon CCS Collects Less CO_2 in Worst Year.” December 2024. (link)

[8] Sources on danger of high concentration CO_2
- NIOSH — IDLH documentation for CO_2 (link)
- OSHA — exposure limits and technical method (link)
- Health and Safety Executive — CO_2 hazard guidance (link)
- Medical review: Permentier et al. (2017), hypercapnia effects (link)

[9] Do, Thai Ngan, Chanhee You, and Jiyong Kim. “Do et al 2022: A CO_2 Utilization Framework for Liquid Fuels and Chemical Production: Techno-Economic and Environmental Analysis.” Energy & Environmental Science 15, no. 1 (2022): 169–84. (link)

[10] Carbon Industrial Usage – Enhanced Oil Recovery EOR (link)

[11] Wikipeida on Enhanced Oil Recovery, EOR (link)

[12] “Why Scaling Direct Air Capture Is Practically Impossible | LinkedIn.” September 2025. (link)

[13] Prof Rasmussen, University of Cambridge, “Why Scaling Direct Air Capture Is Practically Impossible | LinkedIn.” September 2025. (link)

[14] BCG: Shifting the Direct Air Capture Paradigm.” BCG Global, June 2023. (link)

[15] According to US DOE NETL Cost and Performance Baseline for Fossil Energy Plants, Rev.5 (2023), adding 90% post-combustion CCS to an ultra-supercritical coal unit reduces net efficiency from 43.2% to 31.4% (LHV), implying roughly 35–40% higher fuel consumption per net MWh delivered (Table ES-1; Tables 3-14 and 3-22).”