16th International Conference on Greenhouse Gas Control min Technologies, GHGT-16

23rd -27th October 2022, Lyon, France

# Simple, transparent CCS metrics for all

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**Abstract**

Carbon Capture and Storage (CCS) has a well-deserved credibility problem! Industry executives put it at the center of their Environmental, Social, and Governance (ESG) strategies, while environmentalists disparage it as a thinly veiled excuse to continue and expand the use of coal, oil, and natural gas. Meanwhile, policy makers and lobbyists from all sides wrestle over whether and/or how to incentivize it. Coal-fired CCS/Enhanced Oil Recovery (EOR) power generation projects simultaneously claim low-carbon coal, low-carbon electricity, and low-carbon oil. It's no wonder people are distrustful – how can they know what to believe?!

Claims of CCS benefits increasingly bombard the public: cars removed from the road, reductions in steel carbon intensity, barrels of market oil displaced, megatons per year of $CO_2$ capture capacity added, and more. But without a CCS insider's knowledge, the public cannot translate these claims into their associated climate benefit, understand the cost, or compare multiple claims against each other.

This paper first describes the need for and scale required of CCS in the context of basic climate science, the 2015 Paris Agreement, and the International Energy Agency's (IEA) "Net Zero by 2050" scenario. Next, it briefly reviews the status and shortcomings of current CCS industry metrics for emissions reduction, cost, and schedule.

The paper then presents a simple, interactive Excel-based CCS project simulator that allows apples-to-apples comparisons of the climate benefits, costs, and schedules of CCS projects of arbitrary types, capacities, and technologies. The tool favors ease of use and understanding over detail, focusing only on the most important system parameters affecting a CCS project's performance. Its goal is to foster a common understanding and discussion of the impacts and sensitivities of system design choices and performance parameters among any group of interested people with a high school education or more.

The CCS project simulator first defines and calculates standardized emissions metrics for generalized CCS project production, capture, transport, storage, and downstream elements. Input data values may be measured from an actual operating facility or estimated for a planned or hypothetical project. Together these metrics account for all the $CO_2e$ emissions additions and reductions along the project process flow to the ultimate "Project net $CO_2e$ removal rate" metric which represents the project's benefit to the climate.

Building on these emissions characteristics, the CCS project simulator then develops cost metrics both for the individual project and for its contribution to the CCS share of the IEA Net Zero 2050 scenario emissions reductions (7.6 Gigatons per annum). Finally, it provides comparisons of "actual" vs. "planned" emissions, cost, and schedule metrics indicating overall CCS industry technology maturity, as measured by how predictably the project meets its original expectations.

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The paper uses the simulator to showcase a variety of CCS project examples to highlight analyses that it facilitates and insights that it offers. The hope is that it will in some small way provide a forum for industry executives, environmentalists, policy makers, lobbyists, and high school students alike to meet in objective, non-confrontational settings, to clear up misunderstandings about CCS, and to work more constructively together as Global Citizens to solve the tremendous challenge of climate change that we have brought upon ourselves.

*Keywords:* CCS public perception, CCS metrics, Net $CO_2$ emissions, Simulator, Project management, Common understanding, Love

## 1. **Summary**

After recently retiring from a system engineering career in aerospace, I have turned much of my attention to the climate crisis. Long intrigued by Carbon Capture and Storage (CCS), I increased my layman's knowledge through the University of Edinburgh's online course Climate Change: Carbon Capture and Storage [1] offered before and during COP-26. This excellent course convincingly satisfied my initial reservations:

✔ Yes, $CO_2$ can be reliably removed at industrial scale from a wide variety of sources
✔ Yes, $CO_2$ can be safely and reliably transported from capture sites to storage sites
✔ Yes, $CO_2$ can be safely and reliably sequestered for thousands of years with minimal leakage and seismicity risk
✔ Yes, there is sufficient suitable global storage capacity for CCS-based climate change mitigation

In addition, I learned that CCS is essential in all credible scenarios to limit global warming to 2°C or less. In short, CCS is technologically feasible, and the world is counting on it for climate change mitigation. However, the required deployment scale is massive, and three important questions remain to judge whether CCS is up to the task:

1) How much do CCS projects contribute to climate change mitigation?
2) How much will CCS's part in global climate change mitigation cost?
3) Can the global CCS industry be scaled up in time to mitigate climate change?

These questions represent the three pillars of project management (performance, cost, and schedule), but surprisingly, very little concrete data is publicly available to answer them for CCS at the global scale. Available

Project — Carbon Capture and Storage

| Production | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2$e emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production total $CO_2$e | 6.50 | Mtpa |
| Production total new $CO_2$e | 6.50 | Mtpa |
| Production performance | 69.2 | % |

| Capture | | |
|---|---|---|
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2$e | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| Transport | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2$e | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
| Transport performance | 88.9 | % |
| Net $CO_2$ tranported | 3.29 | Mtpa |

| Storage | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storage process $CO_2$e | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2$e emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| Downstream | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2$e intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2$e intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2$e emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2$e emitted | 1.06 | Mtpa |

estimates do not address the questions directly and are often based on models that are difficult to validate. As a result, facts needed to establish a common understanding of CCS's global viability are lacking, leading to divisive and unproductive disagreements with little common basis for discussion.

On the other hand, dozens of commercial scale CCS projects are currently operating, with over one hundred more in development. Operational projects have access to actual emissions reduction, cost, and schedule data, and development project managers are in the best position to predict these parameters for their future facilities. This paper proposes simple, transparent, standardized project-level metrics based on this accessible data, and provides an Excel-based tool to collect and analyze them. These metrics can be aggregated into a common knowledge base to help all interested people assess the feasibility of the global CCS industry to do its part to mitigate climate change, at an affordable cost, before it is too late.

## 2. Climate change mitigation background

"Recognizing the need for an effective and progressive response to the urgent threat of climate change on the basis of the best available scientific knowledge", the 193 parties to the United Nations Framework Convention on Climate Change (UNFCCC) 2015 Paris Agreement [2] have committed to the goal of "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change." In recognition of this overwhelming international agreement, this paper adopts these targets.

Global temperature increase is driven by the increase of greenhouse gases (GHGs) in the atmosphere, primarily carbon dioxide ($CO_2$) from the burning of coal, natural gas, and oil in the energy sector, and from methane ($CH_4$) released during their production and use. Figure 1 shows how the increase of $CO_2$ in the atmosphere from 2,263 Gt in 1850 to 3,280 Gt today (update) has increased atmospheric $CO_2$ concentration from 289 to 419 parts per million, causing an increase in global surface temperature of approximately 1.1°C above pre-industrial levels. It takes very large international data collection and modelling efforts to establish accurate estimates for total atmospheric $CO_2$ content and global surface temperature, but determination of $CO_2$ concentration in the atmosphere is relatively straightforward because "Carbon dioxide is indeed well mixed in the atmosphere. This means that if we look at the $CO_2$ concentrations globally, the value is about [the same] everywhere." [Reference 3]. As a result, global $CO_2$ concentration can be measured accurately from a single location, which since 1958 has been the National Oceanographic and Atmospheric Administration's Mauna Loa Observatory (MLO) at an elevation of 3,397 meters on the Mauna Loa Volcano on the Island of Hawai'i.

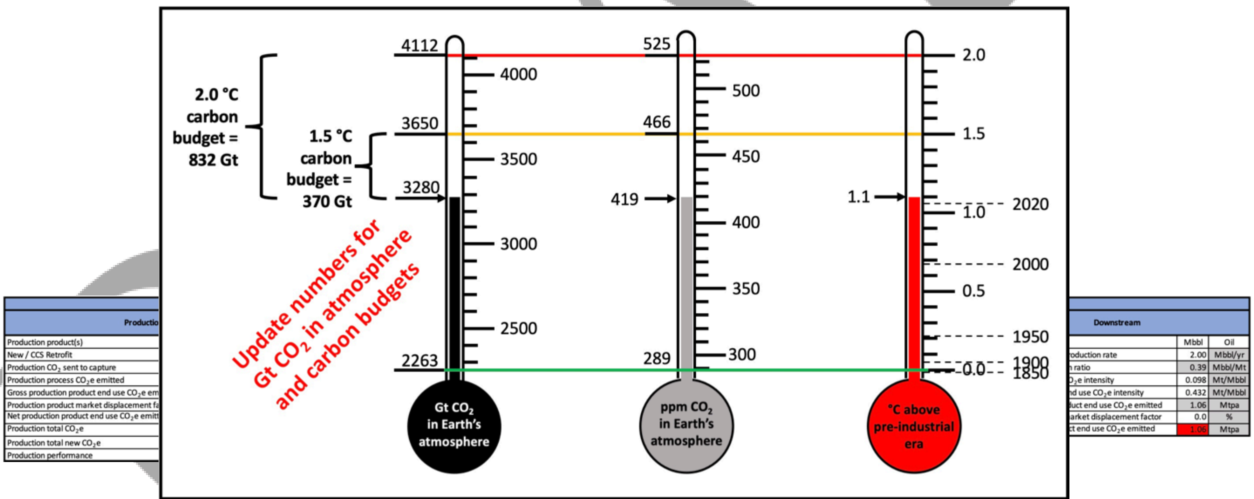


Fig. 1. Trends in global atmospheric $CO_2$ quantity, global $CO_2$ concentration, and global temperature rise.

Figure 2 shows the continuous record of Mauna Loa $CO_2$ measurements since 1958, named the "Keeling Curve" for Charles David Keeling of the Scripps Institute of Oceanography. Keeling directed the program that made the measurements at Mauna Loa from the time the observatory was established until his death in 2005. By documenting the steadily rising carbon dioxide levels, his work supported Svante Arrhenius's 1896 suggestion that humans contributed to the greenhouse effect and global warming. Keeling's son Ralph Keeling currently directs the Scripps $CO_2$ program; for the latest yearly, monthly, weekly, daily, and hourly $CO_2$ levels see https://gml.noaa.gov/ccgg/trends/.

The Earth is currently emitting approximately 42.2 (Gt) of $CO_2$ net per year [4], and the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) estimates that emissions of 500 Gt and 1,350 Gt of $CO_2$ above the January 1, 2020 level would result in 1.5°C and 2.0°C warming, respectively (the 1.5°C and 2.0°C "carbon budgets") [5, Table TS.3]. Thus, if emissions were to level off immediately and remain constant at the current rate, Earth will reach 1.5°C warming in late 2031 and 2.0°C warming in late 2051, after which the global temperature will continue to rise indefinitely.

To prevent global temperature rise above a given level, it is necessary to reach global "net zero" emissions by reducing GHG emissions and/or removing GHGs from the atmosphere, so that emissions become less than or equal to removals before the corresponding budget for that level has been exhausted (currently 370 Gt for the 1.5°C scenario and 832 Gt for the 2.0°C scenario as Figure 1 shows). This holds for all sources of GHG emissions reductions and

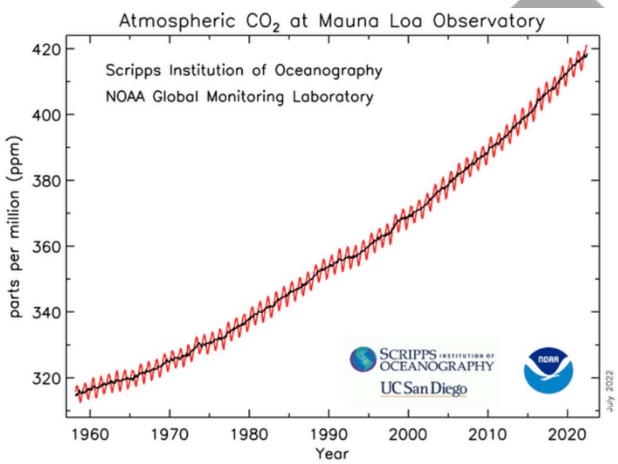


Fig. 2. The Keeling Curve, showing global atmospheric $CO_2$ concentration rise from 1958-2022.

removals combined; of these the energy sector is the largest, followed by agriculture, forestry, and other land use (AFOLU), with other sectors having lesser impacts. This paper considers CCS to be part of the energy sector and so treats only this sector, assuming the other sectors will conduct independent parallel efforts to reduce their emissions as required.

## 3. CCS in energy sector climate change mitigation

| Project | | |
|---|---|---|
| **Production** | | |
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2$e emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production total $CO_2$e | 6.50 | Mtpa |
| Production total new $CO_2$e | 6.50 | Mtpa |
| Production performance | 69.2 | % |

| Carbon Capture and Storage | | |
|---|---|---|
| **Capture** | | |
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2$e | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| **Transport** | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2$e | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
| Transport performance | 88.9 | % |
| Net $CO_2$ tranported | 3.29 | Mtpa |

| **Storage** | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storage process $CO_2$e | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2$e emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| **Downstream** | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2$e intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2$e intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2$e emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2$e emitted | 1.06 | Mtpa |

There are many potential scenarios for the global energy sector to reach net zero emissions, of which the International Energy Agency's "Net Zero by 2050" (NZE 2050) [6] is probably the most well-known. This scenario details a pathway to meet the Paris Agreement's target to limit global temperature rise to 1.5°C by

- reducing combustion of coal, natural gas, and oil
- applying CCS to eliminate most $CO_2$ emissions from remaining coal, natural gas, and oil combustion
- minimizing methane emissions
- using negative-emissions CCS technologies to offset remaining energy sector GHG emissions

Figure 3 illustrates the NZE 2050 scenario's progression to reduce emissions rates from coal, natural gas, oil, and methane and to increase CCS $CO_2$ storage rates from 2020 until they are (nearly) in balance at net zero emissions in 2050. (The term "$CO_2$ equivalent", or "$CO_2$e", accounts for different warming impacts of non-$CO_2$ GHG's such as methane.) The source of the residual +0.6 Gt $CO_2$e net emissions in 2050 is unclear; see Appendix A for derivation.

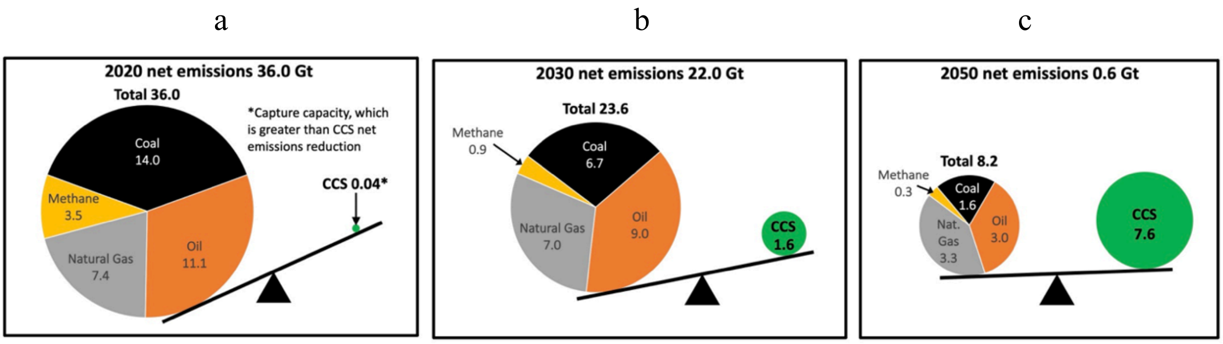


Fig. 3. Coal/oil/natural gas/methane emissions rates and CCS $CO_2$e removal rates in the IEA NZE 2050 scenario. (a) 2020; (b) 2030; (c) 2050

This paper baselines the NZE 2050 scenario, and thus assumes the Figure 3 targets for CCS to achieve a net CCS storage rate of 1.6 Gtpa $CO_2$e by 2030 and 7.6 Gtpa by 2050. The paper addresses production of additional coal, oil, natural gas, and methane emissions by CCS projects themselves, but otherwise assumes that customers, suppliers, and other stakeholders of these industries will conduct parallel efforts to achieve their Figure 3 targets, to reach net zero emissions for the energy sector overall by 2050. The approach applies equally to other scenarios: if coal, oil, gas and methane emissions decline more than indicated then less CCS will be required to reach net zero, and vice versa.

## 4. Existing metrics, CCS industry status, and proposed new top-level metrics

For each of the three questions in Section 1, this section reviews existing publicly available metrics, summarizes CCS industry status in terms of these metrics, and proposes one or more new project-level metrics to help interested people better assess CCS's viability to mitigate climate change. Later sections describe these metrics in more detail, the CCS project simulator implements them, and final sections analyze example CCS projects using them.

### 4.1. *How much do CCS projects contribute to climate change mitigation?*

Climate change mitigation results from net reductions of GHGs in the atmosphere, that is, $CO_2$e removed less

Project

| Production | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2$e emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production total $CO_2$e | 6.50 | Mtpa |
| Production total new $CO_2$e | 6.50 | Mtpa |
| Production performance | 69.2 | % |

Carbon Capture and Storage

| Capture | | |
|---|---|---|
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2$e | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| Transport | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2$e | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
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| Storage | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storage process $CO_2$e | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2$e emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| Downstream | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2$e intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2$e intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2$e emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2$e emitted | 1.06 | Mtpa |

$CO_2$e added. However, CCS projects typically only report the metric "capture capacity", which not only lacks a precise definition, but also exceeds net emissions reduction by typically excluding:

- facility down time
- CCS process emissions
- losses of captured $CO_2$
- emissions from processing and use of production and downstream products (e.g., natural gas from gas processing CCS projects, and Enhanced Oil Recovery (EOR) oil)

The Global CCS Institute (GCCSI) "Global Status of CCS 2021" report [7] lists 27 operating commercial CCS facilities worldwide, with a total combined capture capacity of 40 million metric tonnes per annum (Mtpa). However, due to the factors listed above, their net emissions reductions and therefore their contribution to climate change mitigation are unknown, but certainly less than this (perhaps substantially so).

Since net emissions reductions are the direct measure of a CCS project's contribution to climate change mitigation, this information is critical for interested people to assess the effectiveness of the global CCS industry. As CCS projects have ready access to data on $CO_2$ captured and the factors listed above, they can all report a simple, transparent "Project net $CO_2$e removal rate" metric (in addition to capture capacity) based on actual measured facility values (for operating facilities) or projected parameters (for projects under construction or in development).

## 4.2. *How much will CCS's part in global climate change mitigation cost?*

Massive funding will be required to implement CCS at the scale needed to mitigate climate change. However, CCS projects typically report very little actual cost data, and available models for the total global cost are scarce, vary widely, and are of uncertain accuracy:

- A GCCSI report [8] estimates total CCS capital requirements of USD 0.655 trillion to USD 1.280 trillion, depending on technology "learning rate"
- The GCCSI "Global Status of CCS 2020" [9] referenced an IEA report [10] to claim that meeting Paris goals would require CCS investment of "around USD 9.7 trillion".

These two estimates of unknown accuracy differ by a factor of ten, while cost estimates based on actual project data will reflect reality and better allow all interested people to assess CCS's economic viability. Since CCS projects have ready access to their own cost data, they can all report simple, transparent capital and operating cost metrics, based on actual expenditures (for operating facilities) or projected costs (for projects under construction or in development). These costs may easily be combined with the "Project net $CO_2$e removal rate" metric of Section 4.1 to calculate the cost per ton of net emissions reductions, to which a technology learning rate may be applied to estimate the total cost of CCS implemented from like projects. Alternatively, cost metrics from a representative mix of project types can be combined to generate a composite global cost estimate for CCS.

## 4.3. *Can the global CCS industry be scaled up in time to mitigate climate change?*

Thousands of large, commercial scale CCS projects will be needed to produce the emissions reductions that NZE 2050 requires. Each project is a large, USD billion-scale, multi-year effort with many challenges between initial concept and operation, including financing, public and government approvals, and technical issues, among others.

Project

| Production | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
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| Capture | | |
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As a result, it is not uncommon for projects to be delayed or even cancelled, or for their ultimate emissions reductions to fall short of expectations. Although project implementation should become more routine over time, it is important to be able to predict how quickly global CCS net emissions reductions will realistically increase.

The underlying graphic in Figure 4, from the GCCSI "Global Status of CCS 2021" report [7], shows the 135 projects currently in the global "CCS pipeline": 27 operational, 4 under construction, 102 in development, and 2 suspended. The area of each circle is proportional to the corresponding project's capture capacity, and its horizontal position indicates the project's actual (red circles) or expected (blue circles) date of first operations. The total capture capacity of all 135 projects is 0.149 Gtpa, and the green overlaid circle shows, to scale, the additional 1.45 Gtpa net emissions reductions needed to meet the NZE 2050 scenario's 2030 target of 1.6 Gtpa. Figure 5 shows the CCS pipeline's current and projected capture capacity at its current growth rate (assuming all projects achieve full capacity on schedule) vs. the NZE 2050 net emissions reductions requirement.

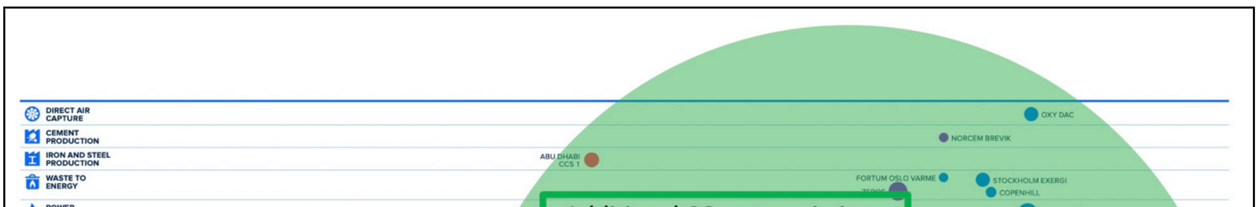


Fig. 4. CCS projects in pipeline (from GCCSI [7]), with NZE 2050 year 2030 target overlay.

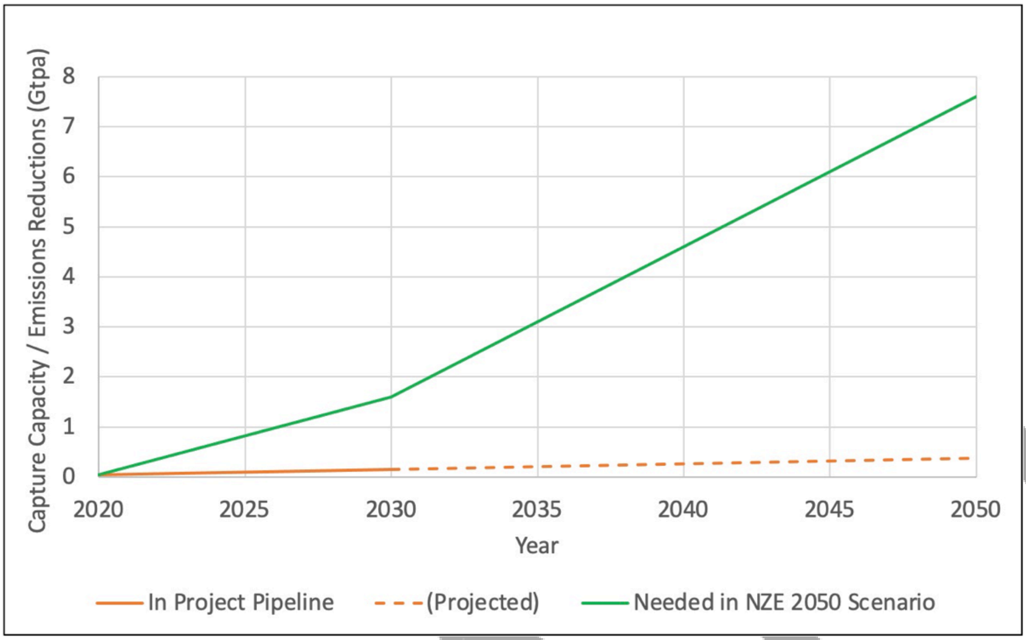



Fig. 5. Capture capacity in development pipeline vs. NZE 2050 CCS net emissions reduction requirement.

Figure 6, from reference [7], shows that the project development pipeline is accelerating, which will be necessary to meet the NZE 2050 targets. However, capture capacities indicated for the projects in development may not all translate into timely net emissions reductions because:

- net emissions reductions are less than capture capacities
- historically, some projects in the pipeline do not reach operational status
- many projects experience emissions reduction performance shortfalls and/or schedule overruns

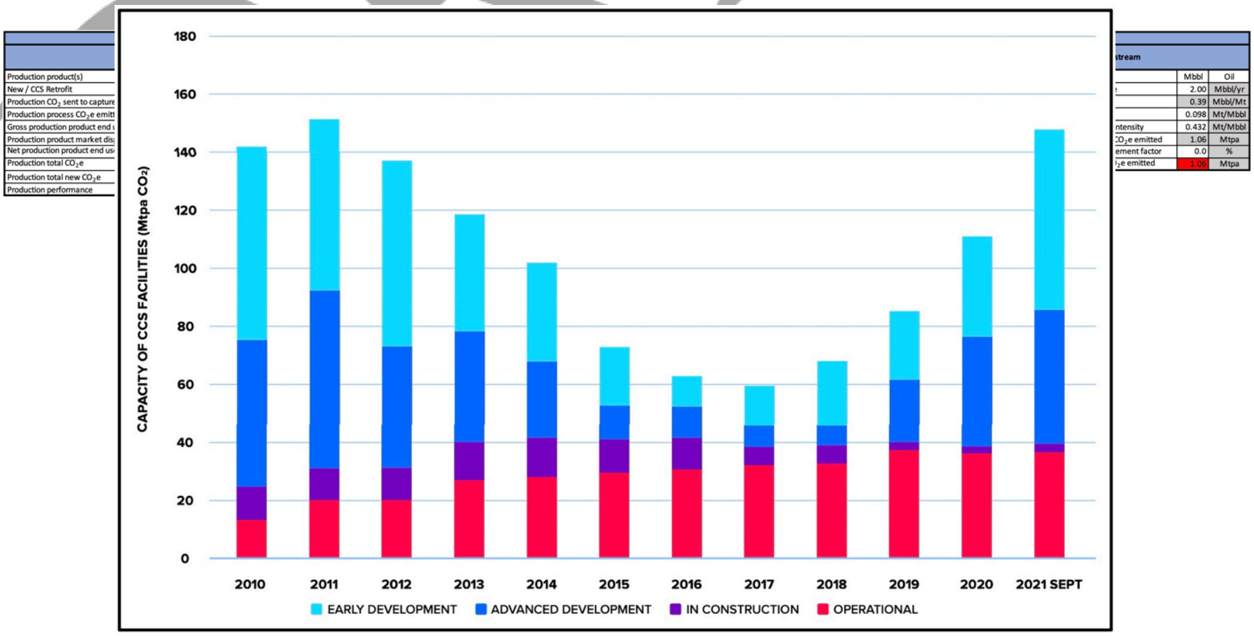


Fig. 6. Pipeline of commercial CCS facilities from 2010 to September 2021 by capture Capacity (from GCCSI [7]).

For example, although operational capture capacity grew from 2011 through 2017, total capacity in the pipeline fell dramatically during this period due to project cancellations, and in 2020 operational capacity actually fell slightly due to the suspension of operations at the Petra Nova facility even as projects in the pipeline increased rapidly.

Comparisons of operational projects' actual vs. predicted emissions reductions and construction schedules will improve the ability of all interested people to predict whether CCS industry growth will approach the NZE 2050 need shown in Figure 5. Since CCS projects have ready access to this data, they can all report simple, transparent predicted and actual values at specified milestones throughout their project life cycles. As CCS technology matures, project implementation should become more predictable and the gap between predicted and actual values should narrow.

## 5. CCS project simulator

The Excel-based CCS project simulator provides quick, intuitive answers to the climate mitigation, cost, and schedule questions from Section 1 for an individual project, and shows the project's contribution to the CCS industry's overall role in solving the climate crisis. The simulator focuses solely on a project's net $CO_2$e emissions reduction and its associated cost and schedule, since net $CO_2$e emissions reductions alone reduce atmospheric $CO_2$e concentration and thus global temperature as Figure 1 shows. It does not address the pathway to be chosen among the many options to replace the services of coal, oil, and natural gas-based products, and therefore does not include any related metrics such as levelized cost of electricity (LCOE), carbon intensity, etc. Such metrics can be misleading because although their decrease implies a decrease in net $CO_2$e emissions, such is not necessarily the case. As an example, a 50% decrease in steel carbon intensity still makes climate change worse if steel production increases by a factor of 3.

Terms in **Bold** in this section match labels in the simulator, which is available with this paper and the "Sample Project" example at https://www.unitedexplorations.world/lets-stop-climate-change/lets-understand-carbon-capture-and-storage-ccs.

### 5.1. *Climate Change Mitigation*

Project

| Production | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2$e emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production total $CO_2$e | 6.50 | Mtpa |
| Production total new $CO_2$e | 6.50 | Mtpa |
| Production performance | 69.2 | % |

Carbon Capture and Storage

| Capture | | |
|---|---|---|
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2$e | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| Transport | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2$e | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
| Transport performance | 88.9 | % |
| Net $CO_2$ tranported | 3.29 | Mtpa |

| Storage | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storage process $CO_2$e | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2$e emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| Downstream | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2$e intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2$e intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2$e emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2$e emitted | 1.06 | Mtpa |

Figure 7 represents the most general case of a CCS project, with a production element, a CCS segment consisting of capture, transport, and storage elements, and a downstream element. This diagram is the basis for the simulator's GHG emissions analysis section, which calculates the **Project net $CO_2$e removal rate** and **Project lifetime CCS $CO_2$e removed** to quantify its contribution to climate change mitigation. The simulator's current implementation only addresses $CO_2$e emissions from the project's operational lifetime and does not include "capital" $CO_2$e emissions from the facility's constructions, although these can easily be added if the data is available. Note that not all projects contain every element. In addition to matching CCS project simulator labels, terms in **Bold** in this section below also match labels on Figure 7.

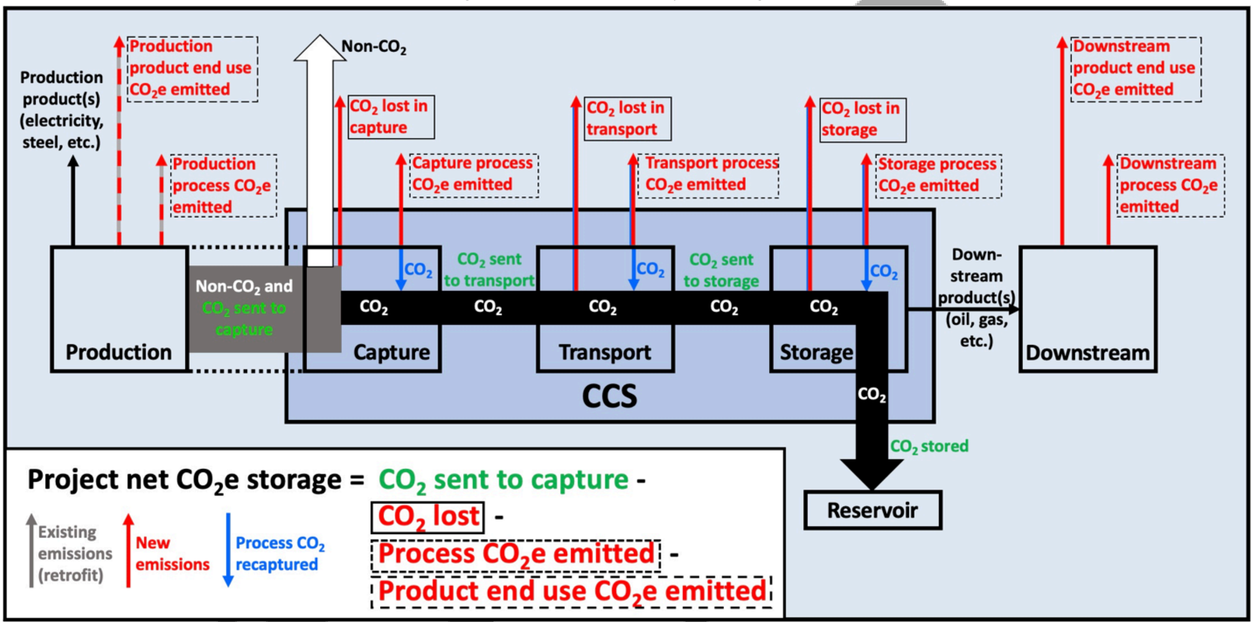
### 5.2. *Climate Change Mitigation*

Figure 7 represents the most general case of a CCS project, with a production element, a CCS segment consisting of capture, transport, and storage elements, and a downstream element. This diagram is the basis for the simulator's GHG emissions analysis section, which calculates the **Project net $CO_2$e removal rate** and **Lifetime net $CO_2$e**

**storage** to quantify its contribution to climate change mitigation. The simulator's current implementation only addresses $CO_2e$ emissions from the project's operational lifetime and does not include "capital" $CO_2e$ emissions from the facility's construction, although this parameter can easily be added if the data is available. This addition would then also support apples-to-apples comparisons of coal/oil/natural gas vs. renewable projects, including the capital emissions associated with development and construction of each.

Note that not all projects contain every element. In addition to matching CCS project simulator labels, terms in **Bold** in this section below also match labels on Figure 7.

Fig. 7. Generalized CCS system diagram.




Each arrow in the diagram is a simulator parameter representing an annual flow of gases or other materials. For example, **Non-$CO_2$ and $CO_2$ sent to capture** accounts for production element down time during the year; likewise, **$CO_2$ lost in capture** includes not only instantaneous $CO_2$ not captured during normal operations, but also $CO_2$

Project

| Production | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2e$ emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2e$ emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2e$ emitted | 0.00 | Mtpa |
| Production total $CO_2e$ | 6.50 | Mtpa |
| Production total new $CO_2e$ | 6.50 | Mtpa |
| Production performance | 69.2 | % |

Carbon Capture and Storage

| Capture | | |
|---|---|---|
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2e$ | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2e$ emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| Transport | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2e$ | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2e$ emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
| Transport performance | 88.9 | % |
| Net $CO_2$ tranported | 3.29 | Mtpa |

| Storage | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storage process $CO_2e$ | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2e$ emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| Downstream | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2e$ intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2e$ intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2e$ emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2e$ emitted | 1.06 | Mtpa |

vented during planned maintenance or unplanned contingency operations throughout the year.

### 5.2.1. *Production Element*

The production element produces one or more **Production product(s)**, such as:

- Electricity · Steel/iron · Natural gas · Heat
- Cement · Hydrogen · Ammonia · Ethanol
- Methanol · Fertilizer · Ethylene oxide · Other Chemicals

As a byproduct, the production element also generates a mixed stream of $CO_2$ and non-$CO_2$ gases. To prevent releasing the $CO_2$ to the atmosphere and worsening climate change, it passes this stream to the CCS segment's capture element for further processing and long-term underground storage (the **Non-$CO_2$ and $CO_2$ sent to capture**).

In addition to the mixed stream of **Non-$CO_2$ and $CO_2$ sent to capture**, the production element emits other **Production process $CO_2$e emissions** to the atmosphere. These may include additional $CO_2$ not sent to capture, such as $CO_2$ from a multi-unit power plant with CCS fitted to only one unit, leakage, or other sources. They also include non-$CO_2$ GHG's emitted by the production process, as well as upstream emissions from the generation of fuels or other materials that the production element uses.

A very important factor is whether the project is a CCS retrofit to an existing production plant or an entire new facility including the production element. For retrofits, the production elements' **Production process $CO_2$e emissions** and **Production product end use $CO_2$e emitted** are already part of global emissions from coal, oil, natural gas, and methane shown in Figure 3, and thus do not contribute to the projects' net emissions. On the other hand, new production elements' **Production process $CO_2$e emissions** and **Production product end use $CO_2$e emitted** add to global emissions and therefore do contribute to the projects' net emissions. In these cases, the projects' impact on the climate is always unfavorable, although CCS makes it less unfavorable than it would be otherwise. Figure 7 represents this distinction by the dashed red and gray arrows for **Production process $CO_2$e emissions** and **Production product end use $CO_2$e emitted**, and the CCS project simulator production element parameters include a dropdown menu item to designate the production element as "Retrofit" or "New".

In some applications, particularly natural gas processing, end use of the production product (i.e., burning of the natural gas) creates additional emissions (**Production product end use $CO_2$e emitted**). Global market demand for some production products may be relatively constant, so that the increase in supply from the modeled project partially "displaces" some of the product from other producers in the market. As a result, global emissions for the production product may increase less than it would without this market displacement, so to account for this effect the CCS project simulator includes a **Production product market displacement factor**. Note that determining an appropriate value for this parameter is a highly inexact science, as it requires accurate modeling not only of the market for the project's specific product, but of the entire global interdependent energy economy as it transitions to net zero emissions. For example, increased natural gas production could displace not only other natural gas, but also new renewable or nuclear energy installations as an unintended consequence, making the energy transition to net zero shown in Figure 3 more difficult. Another factor to keep in mind is that while a non-zero market displacement factor reduces the climate impact of increased coal, oil, or natural gas production at an individual production facility, it likewise diminishes the climate benefit of shutting down a production facility. The simulator includes a similar market displacement factor parameter **Downstream product end use $CO_2$e emitted** as described in Section 5.1.3.

**Project**

| Production | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2$e emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production total $CO_2$e | 6.50 | Mtpa |
| Production total new $CO_2$e | 6.50 | Mtpa |
| Production performance | 69.2 | % |

Carbon Capture and Storage

| Capture | | |
|---|---|---|
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2$e | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| Transport | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2$e | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
| Transport performance | 88.9 | % |
| Net $CO_2$ tranported | 3.29 | Mtpa |

| Storage | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storage process $CO_2$e | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2$e emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| Downstream | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2$e intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2$e intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2$e emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2$e emitted | 1.06 | Mtpa |

Two special project type cases deserve mention. The first is the degenerate case of a standalone production element without a CCS segment or downstream element, such as a power plant without CCS; this is actually by far the most common project type. In this case the production element simply vents all of its emissions to the atmosphere, including the **Non-$CO_2$ and $CO_2$** [not] **sent to capture**. The second case is direct air capture (DAC), which doesn't have a production element at all but instead uses ambient air (0.042% $CO_2$ by volume) as its source of **Non-$CO_2$ and $CO_2$ sent to capture**.

## 5.2.2. *CCS Segment*

The CCS segment reduces the project's net emissions by separating the production element's $CO_2$ from non-$CO_2$ in the capture element, transporting the $CO_2$ to a storage site in the transport element, and storing the $CO_2$ in underground geologic formations that trap it for thousands of years in the storage element. Each of these elements loses and emits some of the initial $CO_2$ from the production element (**$CO_2$ lost)** and generates and emits some additional $CO_2$ and other GHG's in its processes (**Process $CO_2$e emitted)**.

In addition, each element may capture some of its own process $CO_2$ (**Process $CO_2$ recaptured** shown in blue in Figure 7) and add it to the $CO_2$ stream being sent to the storage site, to minimize negative climate impacts of the CCS process itself. In practice this generally occurs only in the capture element, but the CCS project simulator includes **Process $CO_2$ recaptured** parameters for the transport and storage elements as well to allow for the possibility. Note that although **Process $CO_2$ recaptured** increases the volume of $CO_2$ ultimately sent to storage, it does not contribute to **Project net $CO_2$e storage rate** because it represents new $CO_2$ emitted that is immediately captured and stored, and the two cancel each other out. However, because of the increased $CO_2$ volume, **Process $CO_2$ recaptured** in one CCS element contributes to the **$CO_2$ lost** and **Process $CO_2$e emitted** flows in the subsequent CCS elements, as indicated by the partial blue/red arrows for these flows in the transport and storage elements. The CCS project simulator takes these effects into account in calculating **Project net $CO_2$e removal rate**.

This section touches only very briefly on the functions and varieties of the CCS capture, transport, and storage elements. See reference [11] for a much more detailed treatment of these topics, as well as the technology readiness and costs of the technologies.



**Project**

| Production | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2$e emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production total $CO_2$e | 6.50 | Mtpa |
| Production total new $CO_2$e | 6.50 | Mtpa |
| Production performance | 69.2 | % |

**Carbon Capture and Storage**

| Capture | | |
|---|---|---|
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2$e | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| Transport | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2$e | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
| Transport performance | 88.9 | % |
| Net $CO_2$ tranported | 3.29 | Mtpa |

| Storage | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storage process $CO_2$e | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2$e emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| Downstream | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2$e intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2$e intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2$e emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2$e emitted | 1.06 | Mtpa |

#### 5.2.2.1. *Capture Element*

The purpose of the capture element is to receive the mixed **Non-$CO_2$ and $CO_2$ sent to capture** from the production element, separate out the non-$CO_2$ and vent it to the atmosphere, and deliver the $CO_2$ to the transport element for transmission to the storage site. There are many separation approaches, one of the most common of which uses chemical(s) to preferentially bond with the $CO_2$ and form a carbon-rich solid compound, releasing the other gases. The process then applies energy (generally heat) to the solid compound to release the original chemical for reuse, and produces a near-pure stream of $CO_2$ which it then cleans, dries, compresses, and delivers to the transport element.

Capture process chemistry details, complexity, and energy intensity vary widely depending on the application and facility, primarily as a function of the concentration, and partial pressure of $CO_2$ in the mixed stream of **Non-$CO_2$ and $CO_2$ sent to capture**. This $CO_2$ concentration varies from 0.04% by volume for DAC to over 99% for bioethanol fermentation and production, with concentrations for other applications scattered widely in between. The lower the concentration, the higher the energy, complexity, and cost of separation, which is the most significant driver of the entire CCS operational cost.

As described in Section 5.1.2 above, the capture element loses and emits some of the original $CO_2$ it receives from the production element (**$CO_2$ lost in capture**) and generates and emits some additional $CO_2$e (**Capture process $CO_2$e emitted**). In some facilities, the capture element recaptures a portion of its own process $CO_2$ and injects it back into the $CO_2$ stream being sent to storage (**Capture process $CO_2$ recaptured**).

Finally, some CCS projects implement an integrated production and capture element as indicated by the dotted lines in Figure 7. In these cases, the production element produces some or all of the energy used by the capture process, for example as combustion heat that is an input to the production process, or as electricity that is a production product. As a result, the capture element imposes a parasitic load on the production element, thus reducing its output, increasing its emissions, or both. To allow the CCS project simulator to properly calculate the net $CO_2$e emissions of this type of project, the user must manually determine the amount of the **Production process $CO_2$e emitted** attributable to the parasitic load and allocate it instead to the simulator's **Capture process $CO_2$e emitted** input parameter.

Notice that although the CCS project simulator includes the industry standard "Capture capacity" parameter for reference, this value does not factor into the calculation of **Project net $CO_2$e removal rate**. This is because the

Project

| Production | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2$e emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production total $CO_2$e | 6.50 | Mtpa |
| Production total new $CO_2$e | 6.50 | Mtpa |
| Production performance | 69.2 | % |

Carbon Capture and Storage

| Capture | | |
|---|---|---|
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2$e | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| Transport | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2$e | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
| Transport performance | 88.9 | % |
| Net $CO_2$ tranported | 3.29 | Mtpa |

| Storage | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storage process $CO_2$e | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2$e emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| Downstream | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2$e intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2$e intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2$e emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2$e emitted | 1.06 | Mtpa |

capture capacity parameter is not well defined, is only an estimate of potential project maximum performance, and most importantly, does not represent any actual $CO_2$e emission reductions. To relate actual project performance to the more familiar "capture capacity" metric, the simulator defines the top-level project performance parameter **Capture capacity utilization** as the ratio of actual **Project net $CO_2$e removal rate** to **Capture capacity**, expressed as a percentage.

#### 5.2.2.2. *Transport Element*

The transport element receives the clean, dry, compressed $CO_2$ stream from the capture element and delivers it to the storage site, generally by pipeline, ship, or possibly truck. As described in Section 5.1.2 above, the transport element loses and emits some of the original $CO_2$ it receives from the capture element (**$CO_2$ lost in transport**) and generates and emits some additional $CO_2$e (**Transport process $CO_2$e emitted**). Although uncommon, the transport element could potentially recapture a portion of its own process $CO_2$ and inject it back into the $CO_2$ stream it sends to storage (**Transport process $CO_2$ recaptured**).

#### 5.2.2.3. *Storage Element*

The storage element receives the $CO_2$ from the transport element and pumps it underground or undersea into a deep saline aquifer or depleted oil field for dedicated storage, or into an EOR or EGR field to produce more oil and/or natural gas. As described in Section 5.1.2 above, the storage element loses and emits some of the original $CO_2$ it receives from the transport element (**$CO_2$ lost in storage**) and generates and emits some additional $CO_2$e (**Storage process $CO_2$e emitted**). Although uncommon, the storage element could potentially recapture a portion of its own process $CO_2$ and inject it into the storage site (**Storage process $CO_2$ recaptured**).

### 5.2.3. *Downstream Element*

CCS projects which store their sequestered $CO_2$ in EOR or EGR fields to extend the productive life of these wells include a downstream element to then capture, process, and distribute the produced EOR oil and/or EGR gas for sale. These projects generate and emit some additional $CO_2$e during the oil and/or gas processing and refining processes (**Downstream process $CO_2$e emitted**), and further emissions from end use of the downstream product(s) (**Downstream product end use $CO_2$e emitted**). As it does for production products described in Section 5.1.1, the CCS project simulator applies a **Downstream product market displacement factor** to these products to account for their possible displacement in the global marketplace, and the same caveats apply:

- Determining the appropriate value for the market displacement factor is a highly inexact science
- Modelling of the entire global interdependent energy economy as it transitions to net zero emissions is required
- EOR/EGR downstream products may displace not only like products, but also new renewable or nuclear energy installations as an unintended consequence, making the energy transition to net zero shown in Figure 3 more difficult

## 5.3. *Cost*

The CCS project simulator calculates the cost of the project's CCS $CO_2$e reduction in terms of the capital and operating costs of the CCS facilities used to achieve the reductions, and it calculates the cost of new $CO_2$e emissions (if any) from production and downstream elements in terms of the cost of afforestation that would be required to

Project

| Production | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2$e emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production total $CO_2$e | 6.50 | Mtpa |
| Production total new $CO_2$e | 6.50 | Mtpa |
| Production performance | 69.2 | % |

Carbon Capture and Storage

| Capture | | |
|---|---|---|
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2$e | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| Transport | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2$e | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
| Transport performance | 88.9 | % |
| Net $CO_2$ tranported | 3.29 | Mtpa |

| Storage | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storage process $CO_2$e | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2$e emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| Downstream | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2$e intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2$e intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2$e emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2$e emitted | 1.06 | Mtpa |

counteract these new emissions. Total project costs are the sum of the two.

[It should be noted that the simulator probably underestimates afforestation effectiveness and therefore costs, because it doesn't consider that

- additionality and permanence of $CO_2$ sequestration achieved through afforestation are generally lower than of the elimination of coal/oil/natural gas combustion, or of $CO_2$ sequestration by CCS
- whereas the simulator assumes that $CO_2$ sequestration from afforestation is immediate, in reality it takes decades for newly afforested areas to sequester significant amounts of $CO_2$
- land use for afforestation is likely to compete with agricultural land use, with resulting economic tradeoffs

The simulator could easily incorporate additional factors to account for these effects given scientifically verifiable data to assign the values, with the very likely result that afforestation cost estimates would rise.]

To calculate CCS $CO_2$e removal cost, the simulator uses the input metrics **Construction cost**, **Annual operating cost**, and **Project operational lifetime** to compute the **Project lifetime cost** in the selected **Currency**. All costs are assumed to be adjusted to **Actual project** year values, and **Annual operating cost** is assumed to be constant throughout the life of the project. It then divides **Project lifetime cost** by **Project lifetime CCS $CO_2$e removed** to produce **Project cost/ton CCS $CO_2$e removal**. Finally, it calculates **Total scenario cost for CCS $CO_2$e removal** and **Scenario cost/ton CCS $CO_2$e removal** for mitigating the entire 7,600 Gtpa **CCS portion of scenario mitigation** for the NZE 2050 scenario, assuming that the full mitigation for the scenario is achieved by implementing multiple duplicate copies of this project. For this calculation it first divides the **CCS portion of scenario mitigation** by **CCS $CO_2$e removal rate** to produce the **Number of projects needed for scenario**. It then applies a **Construction cost reduction per 2x capacity** CCS industry "learning rate" factor to the second-of-a-kind and subsequent copies of the project, to account for expected decreases in project implementation costs as the CCS industry matures. (See Reference [8].) This factor is a percentage decrease in **Construction cost** only (**Annual operating cost** is assumed to remain constant for all the projects) for each doubling in industry-wide CCS capacity. Using this factor, the simulator calculates the decreasing **Project lifetime cost** for each project from 1 through **Number of projects needed for scenario**, sums them to produce **Total scenario cost for CCS $CO_2$e removal**, and divides this sum by **Project lifetime CCS $CO_2$e removed** and **Number of projects needed for scenario** to produce **Scenario cost/ton CCS $CO_2$e removal**.

To compute afforestation costs needed to counteract new production and downstream $CO_2$e emissions, the CCS project simulator uses the input parameters **Afforestation unit cost** and **Forest $CO_2$ sequestration rate**. These values characterize the cost per hectare to establish new forest, and the $CO_2$ sequestration rate per hectare per year, respectively, of new forestation for the location and tree species mix that would be used to counteract the project's new emissions. See Reference [12]. Using these values, the **New coal/oil/natural gas/methane $CO_2$e emission rate**, and the **Number of projects needed for scenario**, it calculates the **Project afforestation cost** and **Scenario afforestation cost**. Finally, combining these values with **Project lifetime CCS $CO_2$e removed**, it calculates **Total project cost** and **Project cost/ton total $CO_2$e removal**.

## 5.4. *Schedule*

The CCS project simulator contains the simple schedule input metrics **Construction start date**, **Commission date**, and **Decommission date**. From these values it computes **Construction duration** and **Operational lifetime**.

Project

| Production | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2$e emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production total $CO_2$e | 6.50 | Mtpa |
| Production total new $CO_2$e | 6.50 | Mtpa |
| Production performance | 69.2 | % |

Carbon Capture and Storage

| Capture | | |
|---|---|---|
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2$e | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| Transport | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2$e | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
| Transport performance | 88.9 | % |
| Net $CO_2$ tranported | 3.29 | Mtpa |

| Storage | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storage process $CO_2$e | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2$e emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| Downstream | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2$e intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2$e intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2$e emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2$e emitted | 1.06 | Mtpa |

## 5.5. *CCS Technology Maturity*

The CCS project simulator measures project management predictability of emissions reduction, cost, and schedule parameters to indicate overall CCS industry and technology maturity. To do so it includes separate **Planned project** and **Actual project** worksheet tabs to allow comparisons of planned vs. actual project management performance. Using this approach it calculates

- **Lifetime CCS $CO_2$e removal achieved** (%)
- **Operational lifetime achieved** (%)
- **Construction start delay** (years)
- **Construction schedule expended** (%)
- **Construction budget expended** (%)
- **Lifetime budget expended** (%)

## 6. Examples

This section shows with real-world examples how the CCS project simulator compares CCS projects of all types in a uniform framework, to show their impact on climate change. For each project, the simulator generates a summary graph in the format of Figure 2, showing the project's **New coal/oil/natural gas and methane emission rate**, the **CCS $CO_2$e removal rate** achieved, and the net of the two which represents the project's impact on the climate. It also generates a more detailed graphical view showing the performance and losses in the production element, the CCS segment and its capture, transport, and storage elements, and the downstream element. Finally, the Excel cells contain inputs and formulas to generate all the details. In these cells, inputs are denoted by white backgrounds and computed values and labels are shown with gray backgrounds.

Notice that the element-level **Production performance**, **Capture performance**, **Transport performance**, and **Storage performance** parameters characterize the corresponding elements individually, and that the performance of the project as a whole is the product of these parameters. Thus, in a distributed or hub-and-cluster CCS environment, the climate impact of a proposed new interconnection of existing elements can be projected from the element-level pre-characterized values of these parameters.

### 6.1. *Sample Project*

The Sample Project is based on a hypothetical electricity generation facility with CCS and EOR. It is somewhat representative of a relatively large power plant with CCS, but the numerical values for gas flows and other parameters have been selected to show the simulator's graphical and tabular inputs and outputs most clearly. The project is analyzed twice, once as a CCS retrofit to an existing power plant and once as a new power plant with CCS, to show the difference in climate impact for these two cases.

#### 6.1.1. *Retrofit*

The Sample Project retrofit case reduces overall $CO_2$e emissions to the atmosphere because its **CCS $CO_2$e reduction rate** exceeds its **New coal/oil/natural gas/methane $CO_2$e emissions rate**. To realize the full 2.94 **Mtpa CCS $CO_2$e reduction rate**, afforestation is required to counteract the 1.06 Mtpa **New coal/oil/natural gas/methane $CO_2$e emission rate** resulting from the **Downstream product end use $CO_2$e emitted**. Figures 8, 9, 10, and 11, respectively, show the graphical summary, graphical details, Excel summary, and Excel details for this case.

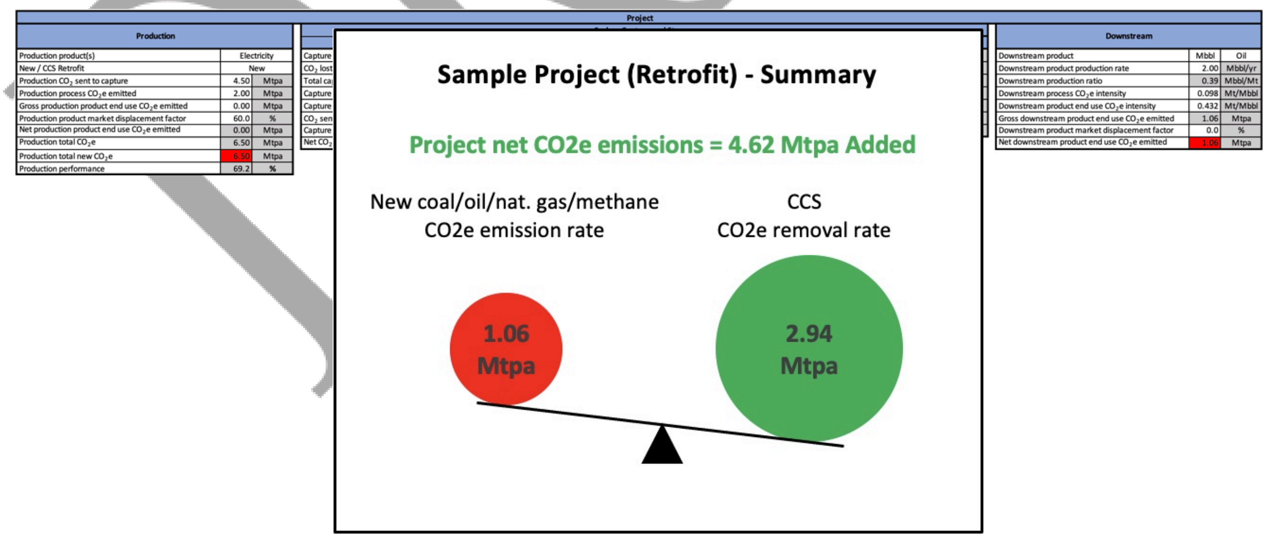



Fig. 8. Sample Project retrofit, graphical summary.

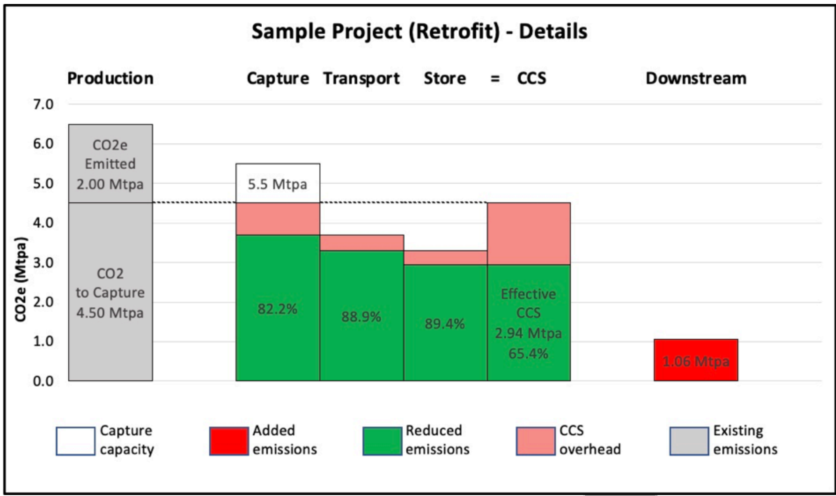



Fig. 9. Sample Project retrofit, graphical details.

| Emissions | | |
|---|---|---|
| New coal/oil/nat. gas/methane $CO_2$e emission rate | 1.06 | Mtpa |
| CCS $CO_2$e removal rate | 2.94 | Mtpa |
| Project net $CO_2$e removal rate | 1.88 | Mtpa |
| Capture capacity utilization | 53.5 | % |
| Project lifetime CCS $CO_2$e removed | 88.2 | Mt |

| Cost | | |
|---|---|---|
| Currency | USD | |
| Construction cost | 3,000 | MUSD |
| Annual operating cost | 50 | MUSD |
| Project lifetime cost | 4,500 | MUSD |
| Project cost/ton CCS $CO_2$e removal | 51.0 | USD/t |
| CCS portion of scenario mitigation | 7,600 | Mtpa |
| Number of projects needed for scenario | 2,585 | projects |
| Construction cost reduction per 2x capacity | 10 | % |
| Total scenario cost for CCS $CO_2$e removal | 6.6 | TUSD |
| Scenario cost/ton CCS $CO_2$e removal | 29.1 | USD/t |
| Afforestation unit cost | 50 | USD/ha |
| Forest $CO_2$ sequestration rate | 18.0 | t/ha/yr |
| Afforestation to offset new project emissions | 58.9 | kha |
| Afforestation to offset new scenario emissions | 152.2 | Mha |
| Project afforestation cost | 2.9 | MUSD |
| Scenario afforestation cost | 7.6 | BUSD |
| Total project cost | 4,502.9 | MUSD |
| Project cost/ton total $CO_2$e removal | 51.0 | USD/t |
| Total scenario cost | 6.7 | TUSD |

| Schedule | | |
|---|---|---|
| Construction start date | 1/1/25 | CE |
| Commission date | 1/1/30 | CE |
| Decomission date | 1/1/60 | CE |
| Construction duration | 5.0 | years |
| Project operational lifetime | 30.0 | years |

| CCS Industry Technology Maturity | | |
|---|---|---|
| Lifetime CCS $CO_2$e removal achieved | 100.0 | % |
| Operational lifetime achieved | 100.0 | % |
| Construction start delay | 0.0 | years |
| Construction schedule expended | 100.0 | % |
| Construction budget expended | 100.0 | % |
| Lifetime budget expended | 100.0 | % |

Fig. 10. Sample Project retrofit, Excel summary.

Project — Carbon Capture and Storage

| Production | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | Retrofit | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2$e emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production total $CO_2$e | 6.50 | Mtpa |
| Production total new $CO_2$e | 0.00 | Mtpa |
| Production performance | 69.2 | % |

| Capture | | |
|---|---|---|
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2$e | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| Transport | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2$e | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
| Transport performance | 88.9 | % |
| Net $CO_2$ tranported | 3.29 | Mtpa |

| Storage | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storag rocess $CO_2$e | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2$e emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| Downstream | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2$e intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2$e intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2$e emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2$e emitted | 1.06 | Mtpa |

Fig. 11. Sample Project retrofit, Excel details.

## 6.1.2. *New plant*

The Sample Project new power plant case increases overall $CO_2$e emissions to the atmosphere because its **New coal/oil/natural gas/methane CO2e emission rate** exceeds its **CCS $CO_2$e reduction rate**. In addition to the afforestation required to counteract the **New coal/oil/natural gas/methane $CO_2$e emission** rate resulting from the **Downstream product end use $CO_2$e emitted** in the retrofit case, additional afforestation is required to counteract the **New coal/oil/natural gas/methane $CO_2$e emission** resulting from new production element emissions. Figures 12, 13, 14, and 15, respectively, show the graphical summary, graphical details, Excel summary, and Excel details for this case.

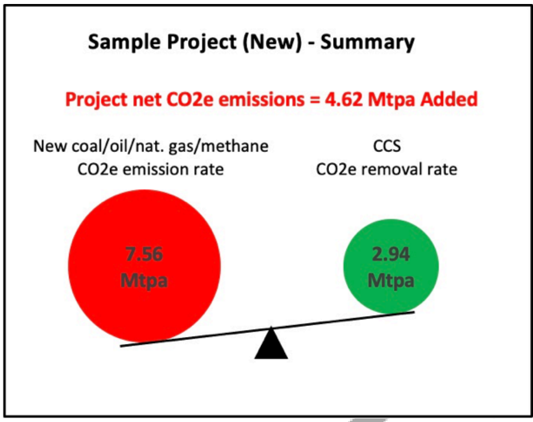
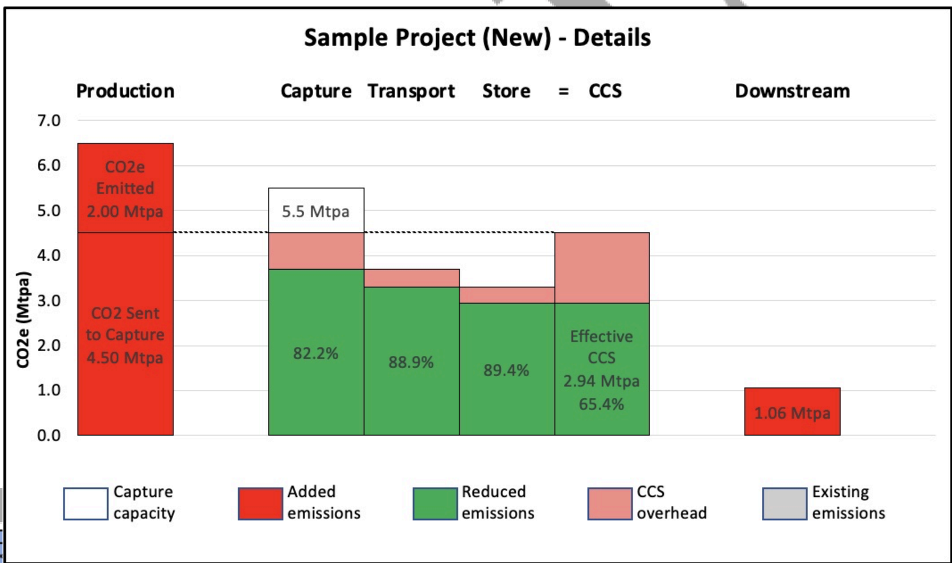



Fig. 12. Sample Project new plant, graphical summary.




| | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2$e emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production total $CO_2$e | 6.50 | Mtpa |
| Production total new $CO_2$e | 6.50 | Mtpa |
| Production performance | 69.2 | % |

| | | |
|---|---|---|
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2$e | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2$e | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
| Transport performance | 88.9 | % |
| Net $CO_2$ tranported | 3.29 | Mtpa |

| | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storage process $CO_2$e | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2$e emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| Downstream | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2$e intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2$e intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2$e emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2$e emitted | 1.06 | Mtpa |

Fig. 13. Sample Project new plant, graphical details.

Fig. 14. Sample Project new plant, Excel summary.

| Emissions | | |
|---|---|---|
| New coal/oil/nat. gas/methane $CO_2$e emission rate | 7.56 | Mtpa |
| CCS $CO_2$e removal rate | 2.94 | Mtpa |
| Project net $CO_2$e removal rate | -4.62 | Mtpa |
| Capture capacity utilization | 53.5 | % |
| Project lifetime CCS $CO_2$e removed | 88.2 | Mt |

| Cost | | |
|---|---|---|
| Currency | USD | |
| Construction cost | 3,000 | MUSD |
| Annual operating cost | 50 | MUSD |
| Project lifetime cost | 4,500 | MUSD |
| Project cost/ton CCS $CO_2$e removal | 51.0 | USD/t |
| CCS portion of scenario mitigation | 7,600 | Mtpa |
| Number of projects needed for scenario | 2,585 | projects |
| Construction cost reduction per 2x capacity | 10 | % |
| Total scenario cost for CCS $CO_2$e removal | 6.6 | TUSD |
| Scenario cost/ton CCS $CO_2$e removal | 29.1 | USD/t |
| Afforestation unit cost | 50 | USD/ha |
| Forest $CO_2$ sequestration rate | 18.0 | t/ha/yr |
| Afforestation to offset new project emissions | 420.0 | kha |
| Afforestation to offset new scenario emissions | 1,085.7 | Mha |
| Project afforestation cost | 21.0 | MUSD |
| Scenario afforestation cost | 54.3 | BUSD |
| Total project cost | 4,520.9 | MUSD |
| Project cost/ton total $CO_2$e removal | 51.2 | USD/t |
| Total scenario cost | 6.7 | TUSD |

| Schedule | | |
|---|---|---|
| Construction start date | 1/1/25 | CE |
| Commission date | 1/1/30 | CE |
| Decomission date | 1/1/60 | CE |
| Construction duration | 5.0 | years |
| Project operational lifetime | 30.0 | years |

| CCS Industry Technology Maturity | | |
|---|---|---|
| Lifetime CCS $CO_2$e removal achieved | 100.0 | % |
| Operational lifetime achieved | 100.0 | % |
| Construction start delay | 0.0 | years |
| Construction schedule expended | 100.0 | % |
| Construction budget expended | 100.0 | % |
| Lifetime budget expended | 100.0 | % |

Fig. 15. Sample Project new plant, Excel details.

## 6.2. *Petra Nova coal fired electricity generation*

- Retrofit benefits climate mitigation
- Less EOR oil produced per day than anticipated (6,000 bbd vs. 15,000 expected?)
- Cost/ton removed higher than anticipated due to premature suspension resulting from low oil prices making EOR unprofitable. As a result capital construction costs were spread across fewer years of operation.

## 6.3. *Boundary Dam coal fired electricity generation*

- Retrofit benefits climate mitigation?
- Captured less $CO_2$ than anticipated due to multi-month CCS equipment shutdown in 2021 while waiting for compressor replacement; $CO_2$ vented to atmosphere during this time?

## 6.4. *Shute Creek natural gas processing*

- Retrofit vs new benefits vs hurts climate mitigation (which is it?)
- End product natural gas use hurts climate mitigation
- Despite claimed 7 Mtpa capture capacity, CCS operations only occur when oil price makes EOR profitable; $CO_2$ vented to atmosphere at other times?

## 6.5. *Gorgon natural gas processing*

- New plant hurts climate mitigation
- End product natural gas use hurts climate mitigation
- CCS commissioning delayed from 2016-2019 ($CO_2$ vented to atmosphere during that time?)
- CCS operating significantly below stated capture capacity since commissioning in 2019

Project

| Production | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2$e emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production total $CO_2$e | 6.50 | Mtpa |
| Production total new $CO_2$e | 6.50 | Mtpa |
| Production performance | 69.2 | % |

Carbon Capture and Storage

| Capture | | |
|---|---|---|
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2$e | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| Transport | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2$e | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
| Transport performance | 88.9 | % |
| Net $CO_2$ tranported | 3.29 | Mtpa |

| Storage | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storage process $CO_2$e | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2$e emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| Downstream | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2$e intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2$e intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2$e emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2$e emitted | 1.06 | Mtpa |

- loss of injectivity at the project's two water injection wells, believed to be related to plugging of the injection wells with "higher than expected solids production" from the four water production wells

## 6.6. *Wabash fertilizer production*

## 6.7. *Summit Carbon Solutions ethanol production*

- Good example to demonstrate analysis of hub and cluster environment, with multiple ethanol $CO_2$ point sources connected via new pipeline network to multiple storage sites

### 6.8. *BASF Antwerp petrochemicals production*

### 6.9. *Air Liquide Rotterdam hydrogen production*

### 6.10. *BASF Antwerp petrochemicals production*

### 6.11. *Air Liquide Rotterdam hydrogen production*

### 6.12. *Stockholm Exergi waste to energy*

### 6.13. *Abu Dhabi CCS 1 iron and steel production*

### 6.14. *Norcem Brevik cement production*

### 6.15. *Oxyventures / Carbon Engineering direct air capture*

- Good example to show DAC costs relative to other technologies processing gas streams with higher $CO_2$ partial pressures
- Good example to show actual data for EOR vs. dedicated geological storage, since this project will do bothxs

#### 6.15.1. *Dedicated geologic storage option*

#### 6.15.2. *Enhanced oil recovery option*

## 7. **Conclusion**

This paper has presented a framework and tool for analyzing and comparing the climate benefits, costs, and implementation feasibility of CCS projects of arbitrary applications and technologies, along with analyses of selected real-world examples using the tool from both currently operating and proposed projects. The framework proposes metrics focused purely on $CO_2$e emissions reductions without regard to how to replace the services provided by coal, oil, and natural gas, since $CO_2$e emissions reductions alone mitigate climate change. Other frameworks, tools, and metrics are possible, and I welcome comments, criticisms, and alternative proposals. However, regardless of metrics particulars, details, and formats, the global CCS community must transparently share basic project emissions reduction, cost, and schedule performance data to enable informed decisions to prevent the devastating impacts of climate change on the environments and peoples of the world. Ideally projects will share this data voluntarily, but if not, project approval and funding could be made contingent on this transparency.

Project

| Production | | |
|---|---|---|
| Production product(s) | Electricity | |
| New / CCS Retrofit | New | |
| Production $CO_2$ sent to capture | 4.50 | Mtpa |
| Production process $CO_2$e emitted | 2.00 | Mtpa |
| Gross production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production product market displacement factor | 60.0 | % |
| Net production product end use $CO_2$e emitted | 0.00 | Mtpa |
| Production total $CO_2$e | 6.50 | Mtpa |
| Production total new $CO_2$e | 6.50 | Mtpa |
| Production performance | 69.2 | % |

Carbon Capture and Storage

| Capture | | |
|---|---|---|
| Capture capacity | 5.50 | Mtpa |
| $CO_2$ lost in capture | 0.25 | Mtpa |
| Total capture process $CO_2$e | 1.50 | Mtpa |
| Capture process $CO_2$ recaptured | 0.95 | Mtpa |
| Capture process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to transport | 5.20 | Mtpa |
| Capture performance | 82.2 | % |
| Net $CO_2$ captured | 3.70 | Mtpa |

| Transport | | |
|---|---|---|
| $CO_2$ lost in transport | 0.025 | Mtpa |
| Total transport process $CO_2$e | 0.55 | Mtpa |
| Transport process $CO_2$ recaptured | 0.00 | Mtpa |
| Transport process $CO_2$e emitted | 0.55 | Mtpa |
| $CO_2$ sent to storage | 5.18 | Mtpa |
| Transport performance | 88.9 | % |
| Net $CO_2$ tranported | 3.29 | Mtpa |

| Storage | | |
|---|---|---|
| $CO_2$ lost in storage | 0.05 | Mtpa |
| Total storage process $CO_2$e | 0.50 | Mtpa |
| Storage process $CO_2$ recaptured | 0.00 | Mtpa |
| Storage process $CO_2$e emitted | 0.50 | Mtpa |
| Gross $CO_2$ stored | 5.13 | Mtpa |
| Storage performance | 89.4 | % |
| Net $CO_2$ stored | 2.94 | Mtpa |

| Downstream | | |
|---|---|---|
| Downstream product | Mbbl | Oil |
| Downstream product production rate | 2.00 | Mbbl/yr |
| Downstream production ratio | 0.39 | Mbbl/Mt |
| Downstream process $CO_2$e intensity | 0.098 | Mt/Mbbl |
| Downstream product end use $CO_2$e intensity | 0.432 | Mt/Mbbl |
| Gross downstream product end use $CO_2$e emitted | 1.06 | Mtpa |
| Downstream product market displacement factor | 0.0 | % |
| Net downstream product end use $CO_2$e emitted | 1.06 | Mtpa |

In hopes that it may be of some use, i offer this Work from One Global Citizen to All Others, that We May Come Together in Harmony to Solve the problem of climate change and thus Preserve the Natural Awe and Beauty of Our Shared Home, Our Earth. 😀 🌍

**Acknowledgements**

University of Edinburgh: Erika Palfi, Mathieu Lucquiaud, MennatAllah Labib, Mark Wilkinson, David Mullen
United States Environmental Protection Agency: Eric Bollerud
United States Department of Energy: Greg Cooney, Jose Benitez, John Litynski, Timothy Skone, Anhar Karimjee
Global CCS Institute: Dominic Rassool, David Kearns, Jeff Erikson
Citizens' Climate Lobby: Bill Hafker, Larry Kremer, Charles Gabrys, Ben Knuth, Jessica Roney
Legal: Marc Kaufman
Johns Hopkins University Applied Physics Laboratory: Larry Zanetti, Larry Paxton, Carey Lisse, Bobby Armiger, Marisa Hughes, Bart Paulhamus, Shelby Anderson, Spencer Langevin
Airbus/Airseas: Eric Lesage, Stéphanie Lesage
Ahsante: Julius White
Chesapeake Bay Foundation Clagett Farm: Dave Vernon, David Laughlin, Michael Heller
Gaylord Brooks: Steve Smith
Medical: Anca Zinnes, Kathi Kolbi
Family: Jeanne de Cervens, Wilson Ballard, Bahji Ballard, Robert Turner

## Appendix A. Derivation of NZE 2050 emissions in 2020, 2030, and 2050

Figure 16 below shows the sources of the data used to derive quantities of $CO_2$e emissions in the NZE 2050 scenario [6] for years 2020, 2030, and 2050.



Project

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|---|---|---|
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| Production $CO_2$ sent to capture | 4.50 | Mtpa |
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| | Native Units | | | | Gtpa $CO_2$e | | |
|---|---|---|---|---|---|---|---|
| | 2020 | 2030 | 2050 | Units | 2020 | 2030 | 2050 |
| Coal | 5250 | 2500 | 600 | Mtce | 14.0 | 6.7 | 1.6 |
| Oil | 90 | 72 | 24 | mb/d | 11.1 | 8.9 | 3.0 |
| Natural Gas | 3900 | 3700 | 1750 | bcm | 7.4 | 7.0 | 3.3 |
| Methane | 115 | 30 | 10 | Mt $CH_4$ | 3.5 | 0.9 | 0.3 |
| CCS | -0.04 | -1.6 | -7.6 | Gtpa | -0.04 | -1.6 | -7.6 |
| | | | | Net $CO_2$e emissions | 36.0 | 21.9 | 0.6 |

Data sources:

- NZE 2050 [5], pp. 57-58
- NZE 2050 [5], p. 54
- NZE 2050 [5], p. 79
- $CO_2$ Emissions by Fuel [11]
- Computed value
- Label

Fig. 16. Data sources for derivation of NZE 2050 emissions.

As indicated on the left, the scenario directly provides all the values for all three years in terms of “native units”:

- coal - megatons coal equivalent (Mtce)
- oil - millions of barrels per day (mb/d)
- natural gas - billions of cubic meters (bcm)
- methane - megatons of methane (Mt $CH_4$)
- CCS - gigatons per year $CO_2$e emissions reductions (Gtpa $CO_2$e)

The “Our World in Data: $CO_2$ Emissions by Fuel” website [13] provides 2020 $CO_2$ emissions data for coal, oil, and natural gas, and NZE 2050 provides the 2020 quantity of methane $CO_2$e emitted by the energy sector. To establish emissions values in terms of Gtpa $CO_2$e, the 2020 Gtpa values just mentioned are first used directly (the 2020 CCS value is already in Gtpa). Next the 2030 Gtpa values are calculated by multiplying each 2020 Gtpa value by the ratio of the corresponding 2030 and 2020 “native unit” values; 2050 Gtpa values are calculated similarly. Finally, net $CO_2$e emissions are calculated by summing the Gtpa $CO_2$e emissions for each year. The resulting net CO2e emissions for 2050 using this method are 0.6 Gtpa, whereas by definition they should be 0.0 Gtpa. The reason for this discrepancy is unclear.

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