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Does Direct Air Capture make any sense or are we just "Chasing our Tail"?

By Peter Baldwin, President base-e

Large investments are planned to confirm that the concept works at small scale, but is DAC a realistic way of addressing unachievable global climate targets?

Let's start the conversation with a question: What does the world's climate engineering community do when it becomes apparent that all conceivable engineering and behavioral strategies to reduce CO_2 emissions will fail to meet targets set to limit global temperature rise?

Is there a silver bullet lurking out there that will turn this failure around?

Enter "negative emissions"

Apparently, and from what is being promoted by our global energy planners, the solution to this quandary is "***negative emissions***", that is, carbon dioxide removal (CDR) technologies to make up for the shortcoming of even the most aggressive efforts to limit ongoing CO_2 emissions.

The strategy, they say, is to deploy CDR technologies that can absorb and dispose of both CO_2 already in the atmosphere, so-called "legacy" emissions, and those still being emitted.

The world has effectively given up on achieving the original 1.5°C target global atmospheric temperature rise limit set by the 2015 Paris Accords. And mitigation efforts, sometimes called "behavioral changes", are far from closing the gap between our current trajectory and that required to achieve the fallback target of a 2.0°C limit.

As shown in Figure 1, the world is still cruising along at a "business-as-usual" trajectory of 40+ Gt/yr CO_2, and 50+ Gte total annual GHG emissions. (Note: 1 Gt = 1 billion metric tonne, Gte = Gt CO_2 equivalent).

To achieve 2.0°C temperature rise limit by the end of the century, the goal must be "net zero" GHG emissions by 2050. This defines the need for deployment of effective policies and practices to bring the current 50+ Gte/yr number down to <10 Gte/yr **and** find an incremental 10-20 Gte/yr worth of ***negative emissions*** (green shaded area of chart).

This amounts to a massive ~30 Gte/yr, or 55% required emissions reduction in less than 30 years, **plus** 10-20 Gt/yr of ***carbon dioxide removal*** (CDR) to balance those so-called "residual emissions" from hard to abate industries, activities and locations that cannot otherwise be reduced.

The world's principal electric power generation decarbonization strategy is to eliminate the use of fossil fuels in favor of renewables. That rhetoric aside, the worldwide consensus seems to support a build-out of natural gas turbine capacity through 2030/35 to meet the added demand of expanded electrification and provide necessary back-up of intermittent wind and solar energy.

Although there is some recent Front End Engineering Design, or "FEED", activity on the application of carbon capture and sequestration to combined cycle plants – both as retrofits and new builds - existing and planned gas-fired turbine units appear to be unabated, i.e., without deployment of carbon capture.

Are negative emissions for real?

It would appear then, on paper at least, that global energy planners have closed the GHG emissions trajectory gap by offering up large-scale CDR, aka negative emissions.

The portfolio of CDR options, with their estimated CDR potential in millions of tonnes CO_2e per year (Mt/yr) and cost per tonne removed, is illustrated on Figure 2.

Options range from low-potential concepts like afforestation, "carbon negative" plastics and cement, and biomass storage, to major potential contributors such as wetland and soil management, biochar/bio-CCS, and "enhanced weathering", said to have no identified limits.

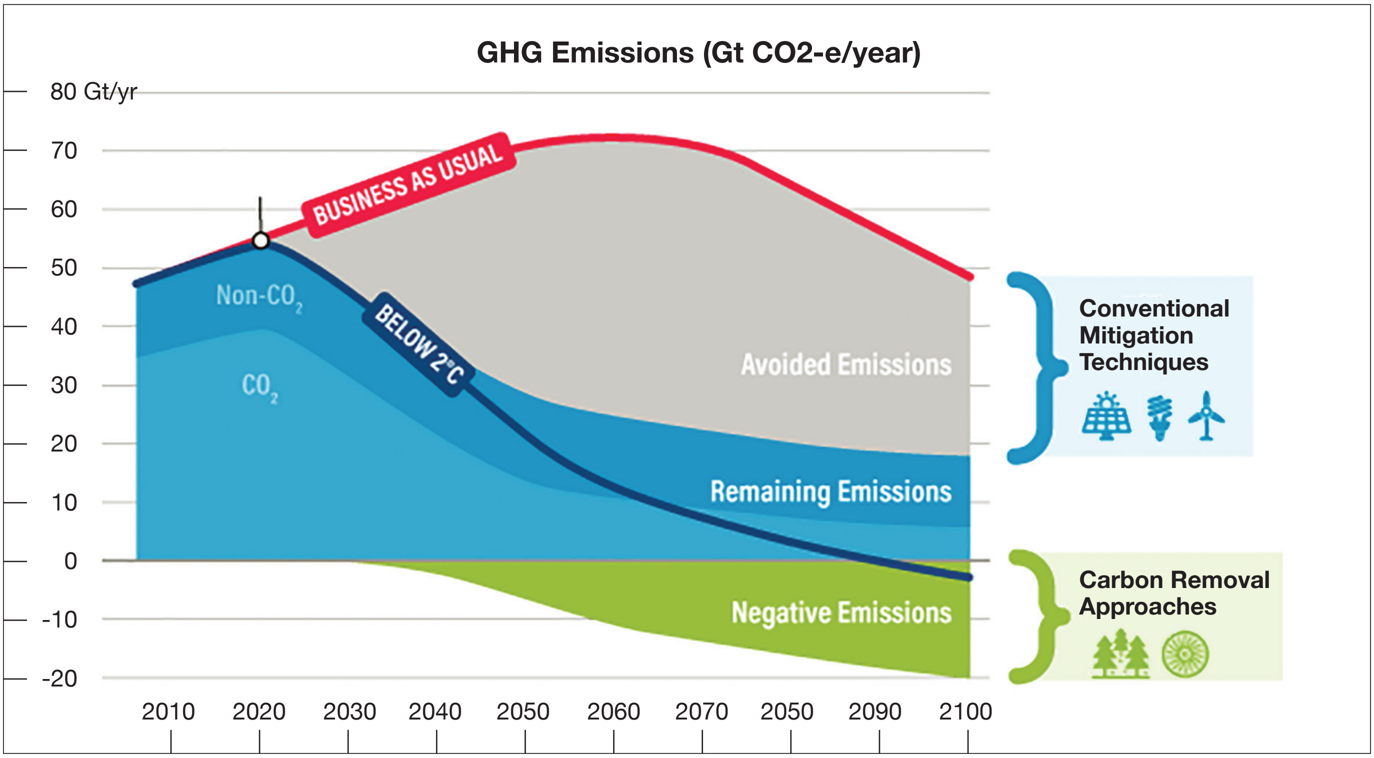

Figure 1. Staying below 2°C of global warming. The pathway to "net zero" and <2°C temperature rise by the end of the century requires an enormous amount of avoided emissions via conventional mitigation techniques, e.g., renewables replacing fossil fuels and improved efficiency plus up to 20 Gt/yr of ***negative* GHG emissions** (green area) to offset both remaining and legacy emissions. Source: World Resource Institute (adapted from UNEP 2016). *For more information visit Wri.org/carbon removal.*

Over and above those options, **Direct Air Capture** (DAC) intended to remove significant carbon dioxide directly from the atmosphere and store it permanently underground, is considered the core tenet behind CDR.

Figure 2 shows that DAC is the most expensive option (most cost estimates are actually much higher than shown there) and that option is also said to have no identified limit in terms of its CDR potential for removal.

These CDR concepts are all identified as "Priority Action" in the International Energy Agency special report, "*Net Zero by 2050, A Roadmap for the Global Energy Sector*", and are embedded in the Net Zero 2050 projections, worldwide.

However, it is noted that the IEA report adds the caveat that in their view half of these reductions, including those resulting from DAC, depend on technologies still "under development".

Moreover, a recent IEA "tracking report" emphasizes that widespread deployment of DAC, along with other more conventional forms of carbon capture, must be underpinned by matching unprecedented growth in CO_2 transport and storage infrastructure.

Under the IEA Net Zero by 2050 scenario, the required global CO_2 storage capacity in place by 2030 would have to ***increase about 30-fold*** compared to approximately only 40 Mt/y in operation today.

Full speed ahead?

The prevailing consensus among global energy planners is to move ahead with deployment of large-scale DAC, with a goal of some **10-20 Gt/yr**, to deal with removal of legacy CO_2 already present in the atmosphere plus ongoing and new emissions that cannot be readily reduced.

For example, the US DOE's Fossil Energy & Carbon Management (FECM) organization will invest up to $96 million to advance a diverse portfolio of CDR approaches that will aid in deploying gigaton-scale removal by 2050.

In their "*Strategic Vision*" released in April 2022, the US DOE office of Fossil Energy and Carbon Management plan for DAC is a **contribution of about 1.0 Gt** per year.

The question before us is whether these goals being set for negative CO_2 emissions, both for the US and globally, realistic and practical? Are they technically achievable, and if so, at what cost?

A tale of two technologies

As described in the IEA report issued in April 2022, entitled "*Direct Air Capture – A Key Technology for Net Zero*", two technologies have been developed to capture CO_2 from the air, solid DAC and liquid DAC.

Solid DAC (S-DAC) which uses solid sorbents operating through an alternating adsorption/desorption cycling process. While adsorption takes place at ambient temperature and pressure, the desorption step happens via a process where CO_2 is released at low pressure (a vacuum) and a moderately elevated temperature (80-100°C).

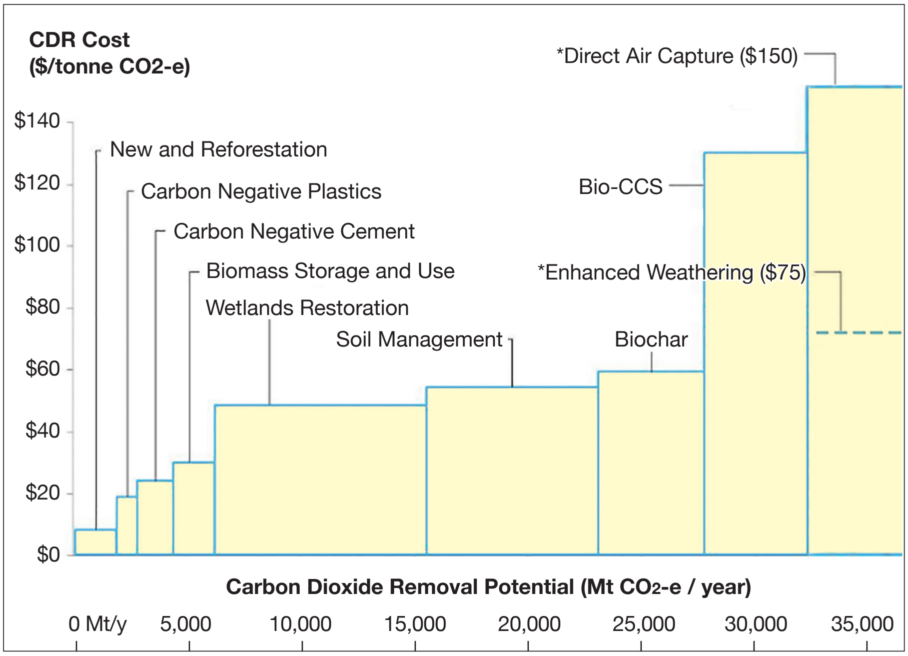

Figure 2. Carbon dioxide removal (CDR) potential. Various methods identified for achieving significant negative emissions vs. estimated cost of removal. *Source*: IEA special report, "Net Zero by 2050, A Roadmap for the Global Energy Sector."
**Note: Potential limits for DAC and Enhanced Weathering removal have not been identffied.*

A single adsorption/desorption system has a CO_2 capture capacity of several tens of tonnes per year (e.g., 50 t/yr). For larger scale operation, a plant would comprise a number of 500 t/yr "modules" arranged into clusters.

Today's largest operating S-DAC plant, the 4000 t/yr (0.000004 Gt/yr) *Climeworks Orca* project in Iceland (https://climeworks.com/roadmap/orca) commissioned late in 2021 contains 8 x 500 t/yr modules arranged into a single cluster.

A larger scale 36,000 t/yr (0.000036 Gt/yr) *Climeworks Mammoth* project currently under construction (also in Iceland) will contain 72 x 500 t/yr modules arranged in a herring-bone pattern of multiple clusters as depicted in Figure 3.

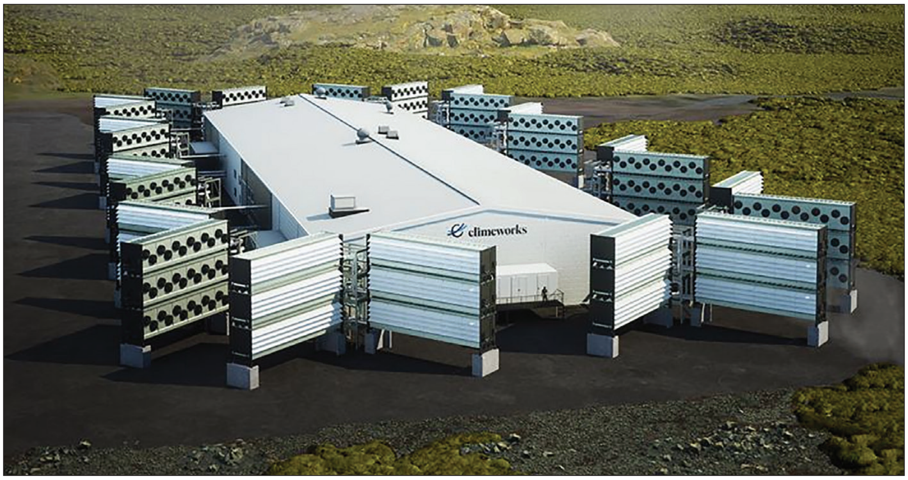

Figure 3. *ClimeWorks Mammoth* S-DAC project. Modular Solid Direct Air Capture technology being applied at the 36,000 t/yr plant now under construction in Iceland is a 9:1 scale-up of company's Orca project already in operation, also in Iceland. *Source:* Climeworks.

To build a gigatonne-scale (1,000,000,000 t/yr CO_2) capture facility using this technology, would require about 28,000 such 36,000 t/yr S-DAC plants!

Liquid DAC (L-DAC) which is based on a continuous-flow two-loop chemical process – a contactor loop and a calciner loop – is more applicable at a utility scale.

With L-DAC systems, air is directed by fans through a "contactor" containing an alkali solution, typically CaOH (aka "slaked lime"), which absorbs the CO_2 to form a carbonate salt (e.g., CaCO3, or common lime) while exhausting the CO_2-depleted air to the environment.

The second loop comprises process units operating at the relatively high temperatures needed to dry the CaCO3 solution, pelletize the lime, and release the captured CO_2 to regenerate the sorbent.

The calciner furnace, or kiln, where the CO_2 is actually released, operates at 900°C (1650°F) and requires considerable input energy provided by natural gas fired in oxygen supplied by a dedicated ASU. Resulting solid residue (CaO) is then directed to a slaker operating at 300°C (572°F) and fed by steam to regenerate the solid alkali sorbent (CaOH) for recycling back to the contactor loop.

A large-scale L-DAC plant is being designed by Canadian-based *Carbon Engineering* to capture around 1 million tonnes (Mt) CO_2/yr (0.001 Gt/yr). Grouping several such plants around a single collection hub would provide a multi-megaton "cluster" capability.

L-DAC vs. S-DAC

Refer to Figure 4 for simplified schematics of solid and liquid DAC process plant operation. They differ in that L-DAC plants operate continuously at steady state whereas S-DAC plants rely on batch operation involving multiple units in parallel.

Both processes require water. Sometimes, depending on site temperature and humidity, an S-DAC can extract needed water from the air. The L-DAC process, however, requires a continuous supply of water.

This may prove to be an issue regarding siting based on local availability and cost of water. Otherwise, in theory, DAC plants can be sited anywhere with access to energy and pipeline transportation for CO_2 storage or utilization.

In IEA's Net Zero Emissions by 2050 scenario, DAC technologies are expected to capture over 85 Mt/yr CO_2 in 2030 and about 1 Gt/yr CO_2 in 2050. Considering that world capacity today is only around 1 Mt/yr, this emphasizes the large and accelerated scale-up required for DAC to meet those targets.

Since L-DAC technology is better suited for scale-up, it most likely will be the technology used in the large plants needed to make any meaningful impact on atmospheric CO_2 levels. Remember, the global scale we are talking about is an end-of-century target removal rate ***on the order of 10-20 Gt per year.***

As mentioned, Canadian-based *Carbon Engineering* is working on design development of a megatonne-scale L-DAC plant. Its initial application is expected for a project in Texas in partnership with *Oxy Low Carbon Ventures* (a subsidiary of oil producer Occidental) in which the captured CO_2 will be used for enhanced oil recovery.

Project timetable calls for start of construction in 2023 with operation to begin in 2025. It is expected that this schedule will be accelerated by added financial incentives in the new so-called ***Inflation Reduction Act of 2022***.

This megatonne size plant, considered prototypical of large-scale commercial installations, could become the model for building 1,000 such plants worldwide over the next 30 years which will be needed to meet the IEA global target of 1.0 Gt/yr removal capacity by 2050.

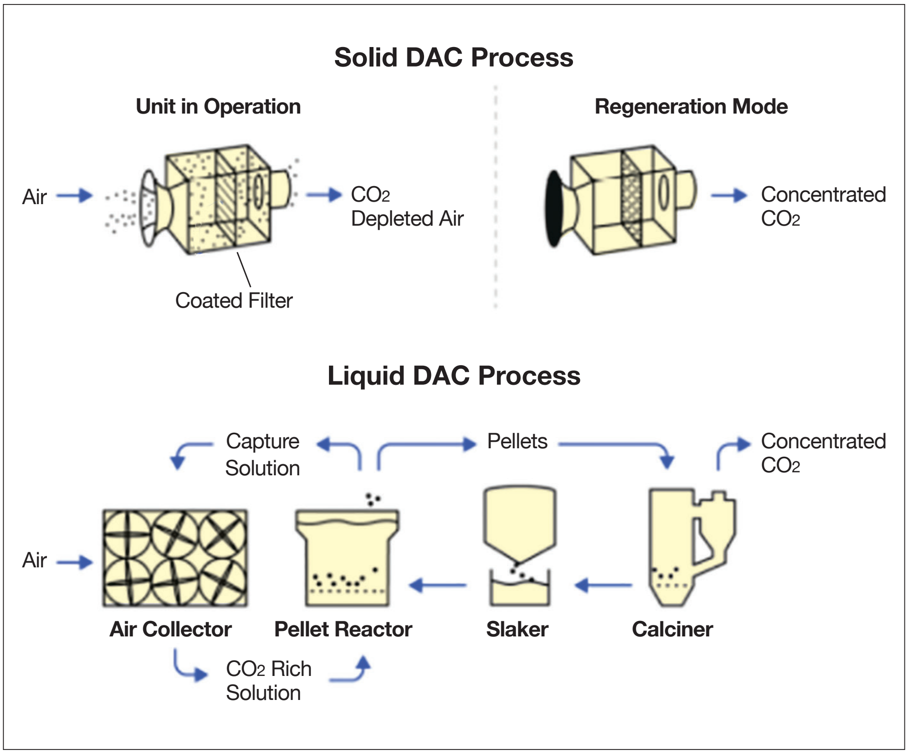

Figure 4. Solid and liquid DAC diagrams. In S-DAC process, air is drawn into the collector where CO_2 is captured by an adsorbent-coated filter. Collector is periodically closed and heated to release the captured CO_2 (regeneration mode). In L-DAC, air passes through a capture solution which reacts with CO_2 and forms carbonate salt pellets which are then heated to release the CO_2, hydrated (slaker), and recycled. *Source:* IEA analysis

L-DAC process flow

Figure 5 shows the process flow diagram of the *Carbon Engineering* megatonne plant based on published design information, including details of the mass and energy balances. (Ref: *"A Process for Capturing* CO_2 *from the Atmosphere"*, David Keith, et. al., June 2018. (https://doi.org/10.1016/j.joule.2018.05.006)

It is noted that plant operation, including the air contactor unit, CO_2 compressor, and air separation unit (ASU) requires almost 56 MW of electrical power supplied by an on-site natural gas fired combined cycle unit, comprised of a 46 MW gas turbine and 9.8MW steam turbine.

The gas turbine is fueled by 6.3 t/h of natural gas. After passing through the HRSG, the gas turbine exhaust is sent to the contactor loop so it too can be stripped of CO_2.

Table 1. DAC Process Power.

Operational power requirements for 112 tph (approx 1 Mt/yr) DAC process plant shown in Figure 5. Power is supplied by 56 MW combined cycle unit.

Power Consumption	
Air Contactor	0.2 MW
CO_2 Absorber	0.4 MW
Pellet Reactor	3.4 MW
$CaCO_2$ Makeup	0.3 MW
Quicklime Mix Tank	0.2 MW
Steam Slaker	3.6 MW
Calciner	0.8 MW
Auxiliary Power	2.6 MW
CO_2 Compressor	22.0 MW
Air Separation Unit	13.3 MW
Total	**55.8 MW**

Power Generation	
Gas Turbine	46.0 MW
Steam Turbine	9.8 MW
Total	**55.8 MW**

Note that CO_2 emissions produced by burning the 13.4 t/h of natural gas to fire the calciner furnace are also added to emissions released from the quicklime, and fed to the CO_2 compressor.

Overall the DAC plant removes 112 tph of CO_2 from the atmosphere, or about 1.0 Mt/yr (at 80% capacity factor) plus 59t/h from the calciner and gas turbine exhausts.

The total CO_2 delivered to the CO_2 compressor is 171 t/h at an unspecified low pressure, assumed to be ~20 psia. The compressor consumes 22MW to deliver the CO_2 at pipeline pressure shown as 151 bar (2215 psia).

Finally, note that the natural gas consumed by the plant for fueling the gas turbine and firing the calciner totals 19.7 t/h. This almost 1,000 GJ/h energy input is needed to remove 112 t/h (or ~0.001 Gt/yr) of CO_2 from the atmosphere, equivalent to *~9 GJ (or ~8.5 x 10^6 Btu) per tonne removed.*

Chasing our tail

Consider what this level of energy cost means for 1,000 such megatonne-scale plants needed by 2050. And 10-20 times that many plants overall (10-20 Gt/yr) will have to be built to meet end-of-century CO_2 removal targets.

Roughly, based on the current annual global natural gas production of around 140 Quads (140 x 10^{15} Btu), it would take almost 60% of the natural gas being produced worldwide to meet the end-of-century 10 Gt/yr target!

If possible to have an all-electric version of the process, with almost 200 MWe input for about 1 Mt/yr (electrical power consumption plus electric heating of calciner furnace), the 10 Gt/yr target would require over 11,000 such plants and over 2.2 ***terawatts*** of dedicated ***clean*** power generating capacity.

This would amount to a consumption of around 19,500 TWh per year - or ***greater than 70% of electric power produced globally!***

And that is ***in addition to*** the enormous input green power that will be needed to produce the green hydrogen forecast for the end of the century.

A March 2022 paper by Long-Innes and Shructrup presents a detailed

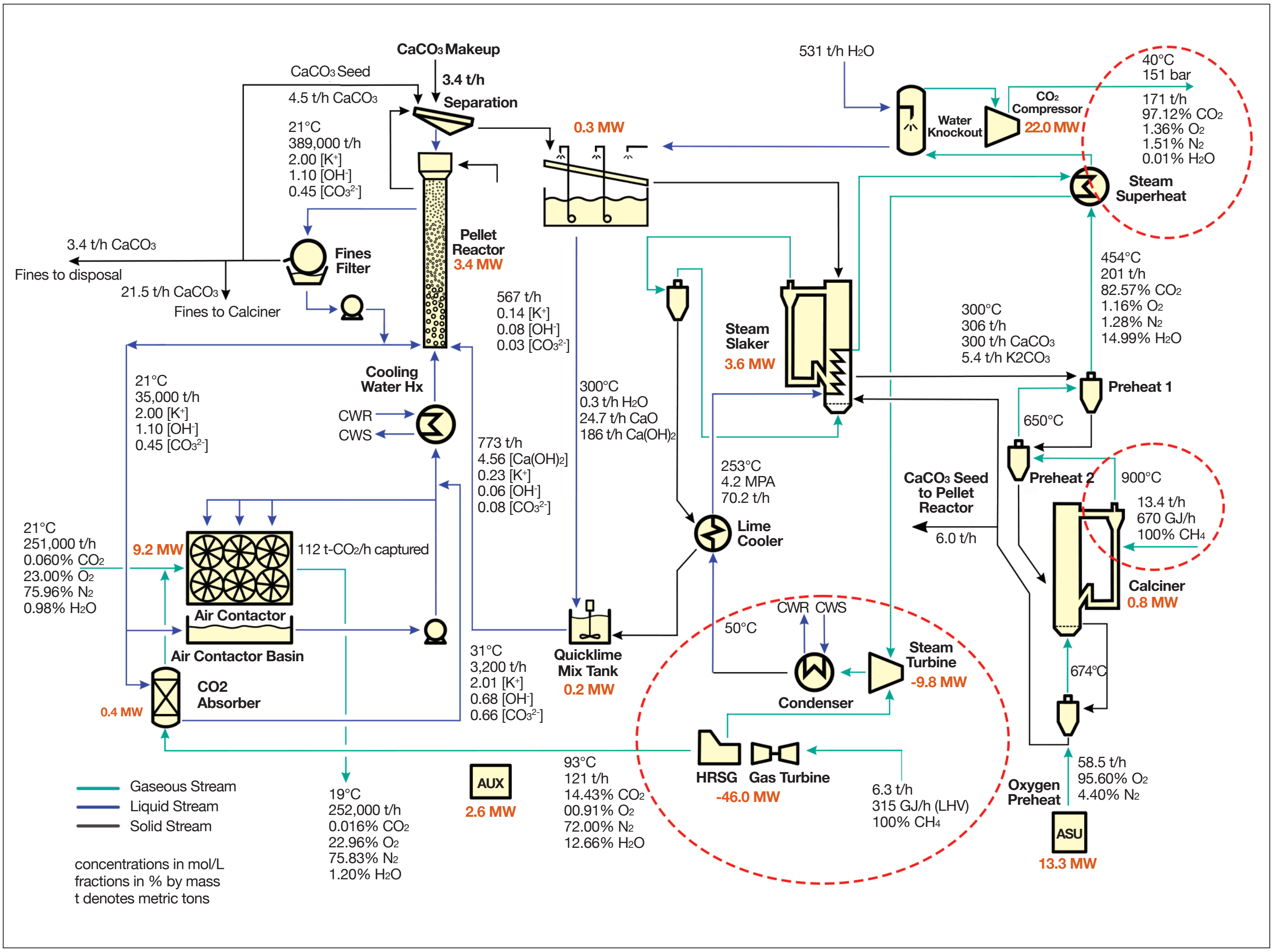

Figure 5. Carbon Engineering plant. Detailed mass and energy balance for plant designed to remove 112 t/hr (~1M t/yr) of CO_2. Total CO_2 captured (1.71 t/hr) includes that collected from gas turbine and calciner furnace exhausts. Plant requires about 56 MW of power and consumes 19.7 t/hr of natural gas (shown as 100% methane). Source: David Keith, et. al. *"A Process for Capturing CO_2 from the Atmosphere"*, June 2018.

thermodynamic analysis of the *Carbon Engineering* megatonne L-DAC process design and points out that "although direct air capture of CO_2 is often presented as a promising technology to help mitigate climate change, ***proposed processes are all highly energy intensive.***"

Refer to "*Thermodynamic loss analysis of a liquid-sorbent direct air carbon capture plant*" at https://www.sciencedirect.com/science/article/pii/S2666386422000583).

Some key observations from the study:

1. The task of direct air capture at rates significant enough to have a global impact (10 Gt/yr) is tremendous, would require large portions of the ***world's current power generation and natural gas*** production**.**
2. At the desired rates of CO_2 removal, the use of DAC systems would ***have a significant impact*** on the world's energy systems.
3. It goes without saying that if DAC is to have a meaningful future, ***substantial improvement in process design and efficiency*** is vital.

The analysis concludes that the **2nd Law efficiency of the process *is only 7.8%.*** This emphasizes the fact that that the leading L-DAC process design is alarmingly wasteful of energy, using almost 13 times the ideal case.

The report also underscores the extent of process improvements needed to make the large-scale deployment of DAC practical and viable. ***Lacking those improvements, we are only chasing our tails!***

At what cost DAC?

Due to its low concentration in air, capturing CO_2 from the atmosphere is considered the most expensive application of carbon capture.

The CO_2 in the atmosphere at 400 ppmv is 100x more dilute than in the flue gas from a natural gas-fired gas turbine power plant at about 4% (40,000 ppmv). And, that is considered dilute compared to coal-fired power generation, with flue gas CO_2 concentration at about 12% (vol).

The cost vs CO_2 concentration curve in the IEA chart, Figure 6, shows the steep increase in capture cost per tonne CO_2 at concentrations below 10% (vol) or 100,000 ppmv.

Based on estimated 2020 costs, the capture cost for DAC is almost 4x the average cost of CO_2 captured in producing blue hydrogen via steam-methane reforming (SMR) of natural gas, and 3x the average cost of carbon capture applied to power generating facilities.

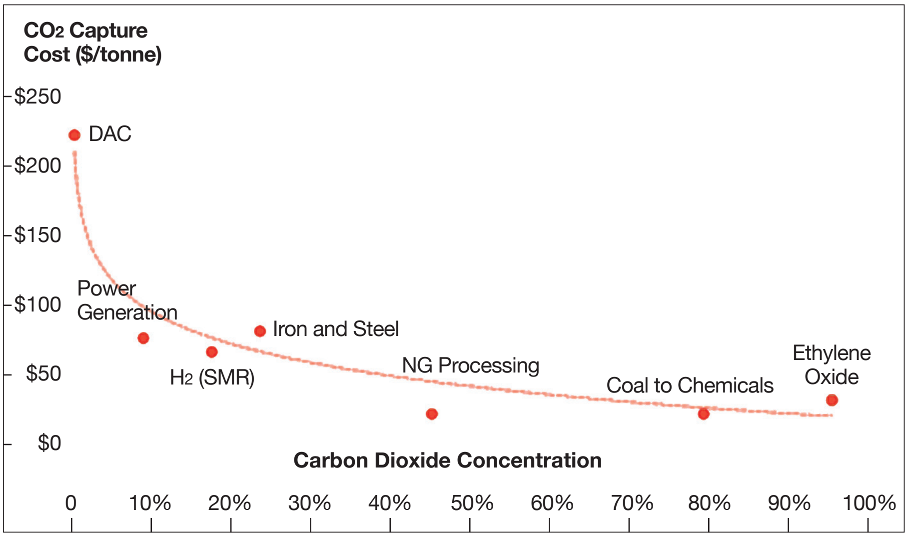

Figure 6. Cost of CO_2 capture vs concentration. Plotted costs are average values ($/tonne CO_2) by application. Cost of direct air capture (DAC) shown to be over 3x that of power generation and steam methane reforming (SMR). Note: gas turbine exhaust contains roughly 4% CO_2 (vol) while air contains about 0.004%. Source: IEA

Capture cost estimates reported in the literature range from $100 to $1,000 per tonne, while cost estimates from main technology providers range from $95 to $230 for L-DAC and $100 to $600 per tonne for S-DAC.

According to IEA estimates, the cost of capture via DAC for large-scale applications (1Mt CO_2/yr) range from $125 to $335/t (chart shows average of $230/t) depending on solid- or liquid-based capture technology, heat and electricity costs, financial assumptions, specific plant configuration.

Cost of capture also depends on whether the captured CO_2 is to be used locally at low pressure or geologically sequestered, requiring compression to the >2215 psia pipeline pressure needed for transport and injection.

Claims that projected DAC costs can be lowered enough to achieve the $100 per tonne industry target are based on highly optimistic assumptions of scale-up efficiencies and of greatly lower green energy costs than those seen escalating in the real world today.

Such favorable cost-of-capture projections also include very optimistic cost recovery assumptions from the sale and utilization of recovered CO_2 emissions.

Even at that aggressive target level, achieving the goal of 10 Gt/yr would ***cost $1 trillion per year*** whether it be in actual costs to industry or spread out to the general public (i.e., socialized) as would be the case if subsidized by government.

The infrastructure plan

In 2021 the US committed $3.5 billion under the *"Infrastructure Plan"* to establish four (4) regional DAC hubs and introduced a "DAC Prize" program offering $100 million for commercial-scale projects and $15 million for pre-commercial projects.

DAC projects in the United States are lining up to take advantage of Infrastructure funds and tax credits:

- Besides the megatonne-scale plant planned by the *Carbon Engineering/Oxy* team in Texas, the California-based Carbon Capture Partnership has launched *"Project Bison"* in Wyoming with first production scheduled for the end of 2023. The announced expansion plan is for a 5 Mt/y cluster (0.005 Gt/yr) by 2030.
- US operator *Continental Resources* will invest $250 million into *Summit's* North Dakota CCS project scheme to handle CO_2 collected from ethanol plants and other industrial sources in Iowa, Nebraska, Minnesota, North Dakota and South Dakota. CO_2 will be transported via pipeline network to a site in North Dakota for permanent sequestration. Initial commitments signed by 31 ethanol facilities for over 8 Mt/yr of CO_2. Initial pipeline capacity of 12 Mt/yr can expand to handle 20 Mt/yr,
- The U.S. DOE expects to fund 12 CCS projects (95%-plus capture) through initial design and select six to share $2.1 billion for detailed design and construction; two at coal-fired power plants, two at gas-fired plants, and two at industrial facilities. Funding requires at least 50% cost share.

A strategic vision

In April, 2022 the US DOE office of Fossil Energy and Carbon Management (FECM) issued its updated "*Strategic Vision*" defining its mission and role in ***achieving net-zero greenhouse gas emissions.***

At the outset of the report, in what is referred to by some as "*The Disclaimer*", the FECM Leadership Team sets forth the following overall guideline to understanding the Strategic Vision and the formidable job at hand:

"The DOE supports projects with large, long-lived assets. In some cases, designing investments for the highest possible value and impact may make the metrics and choices seem ***counter-intuitive from the perspective of 2022.***

"It is imperative to remember these investment strategies are designed to be maximally successful in ***2050 and beyond***, not over the next budget cycle.

"Specifically, searching for and finding ways this work can enable and reinforce broader decarbonization, ***without creating path dependencies that lock into patterns of the past***, is one mission and a major charge of FECM."

Briefly, the report states that: "FECM will invest in advancing ***a diverse portfolio*** of CDR approaches that will aid in gigatonne-scale removal by 2050." Some key points:

- Climate models make it clear that CDR at the ***gigatonne scale*** is required to achieve net-zero by mid-century.
- Diverse CDR approaches will support the objective of DOE's "***Carbon Negative Shot***" of costs ***below $100/net metric tonne*** of CO_2-equivalent (CO_2e).
- Diverse CDR approaches will address emissions from extremely hard-to-decarbonize sectors and eventually address ***legacy emissions***.
- Near-term focus areas include advancing DAC coupled to durable storage.
- To achieve maximum impact with CDR, it is critical to ***couple it to zero-carbon energy***.
- ***Regional Carbon Management Hubs*** sharing transportation and geological storage infrastructure could accelerate CCS while maximizing efficient use of resources.
- ***Several billion dollars of strategic investment*** will be needed over the next decades to ensure critical infrastructure is in place to meet US decarbonization and carbon management goals.

FECM is focused on four key strategies to accelerate the development and deployment of reliable CO_2 transport and storage (T&S) infrastructure:

1. Expand storage infrastructure,
2. Plan for CO_2 transport,
3. Improve T&S performance and reliability,
4. Strengthen T&S synergies.

Electric power strategy

As for the power generation industry, the FECM Strategic Vision states: **"**Our principal electric power strategy is to decarbonize *generation by **eliminating the use of fossil fuels*** while we ***ramp up system capacity*** to support full electrification.

"It is easy to demonize the oil and gas industry in this way, but we will need their active cooperation to deal with the scope and scale of this problem."

The call to address climate change has turned into a cry for eliminating fossil fuels. A more accurate and more inclusive label would be to "***eliminate the emissions*** from fossil fuels".

This would not disenfranchise the Oil & Gas industry and would encourage their involvement.

Such a more inclusive strategy would allow for Point Source Capture (PSC) at the power plant at ***greatly lower capture cost*** and eliminate much of the concern over stranded assets resulting from the transition to renewables.

Given the turmoil in energy markets today, such a definition would provide for greater flexibility in meeting today's market supply/demand challenges.

Closing observations

Concluding with some final observations and frank remarks:

1. The scale of DAC deployment to meet climate target of ***at least 10 Gt/yr*** will dictate the use of L-DAC and require on the order of ***10,000 x 1 Mt/yr plants***,
2. About two-thirds of the climate-related spending of the ***$369 billion*** US *Inflation Reduction*

Act (IRA) will be in the form of tax credits for investments in production of electricity from clean energy sources, carbon capture/transport/storage and other clean energy activities,

3. Estimates are that the IRA will result in reducing CO_2 emissions from ~30% to 45% by 2030 vs. the 2005 all-time peak levels,
4. But 2021 CO_2 emissions attributed to US power sector (~1.55 Gt) were already 35% below 2005 peak level (~2.40 Gt) due largely to coal-to-gas shift and renewables,
5. So 40% reduction from 2005 level amounts to only about 7% reduction in current levels,
6. Numbers reflect the declining impact of coal-to-gas shift and ***emphasize need to deploy CCS on gas-fired turbine fleet*** to realize estimated potential reductions.

The IRA also contains a variety of enhancements to existing tax credits aimed at supporting the developing CCUS industry:

- increases the 45Q tax credit for geological ***sequestration of CO_2 to $85/t*** (up from current $50/t), believed to be threshold level needed to incentivize hard-to-abate industries,
- contains a special rule for DAC facilities under which the 45Q tax credit is valued at approximately ***$180/t captured***.
- lowers the thresholds of "Qualified Facilities": for power plants to ***18,750 t/yr CO_2*** captured (approximately 40 MW high efficiency gas turbine); ***12,500 t/yr for industrial*** facilities and ***1,000 t/yr for DAC facilities***,
- makes 45Q Tax Credits available to tax exempt entities through "Direct Pay", i.e., as a tax refund, as if it were an overpayment of taxes, and
- allows a "Crowd Source Funding" option for some DAC projects.

While the main thrust of these financial incentives is accelerated development of effective carbon capture and storage capacity, the government must not lose sight of the importance of ***reliable and safe pipeline systems*** for transporting the captured CO_2.

As part of any strategy to accelerate development of reliable CO_2 transport, there is a critical ***need for strong federal safety standards*** designed specifically for carbon capture pipelines.

The absence of such standards has led to strong local opposition to the siting of such pipelines in populated areas due to recognized risk of serious accidents.

Pipeline safety becomes even more vital when considering plans for clustering large, L-DAC carbon capture plants and collection hubs among existing industrial facilities.

The challenges and costs associated with managing the 900°C regeneration heat, and collecting the resulting CO_2 from 1 Gt/year clusters, at scale near a hub/pipeline seem underestimated.

Likewise, the ***engineering issues and costs related to CO_2 compression*** in the various studies, if considered at all, are underestimated and need more accurate representation.

L-DAC will require turbo compressors; S-DAC will use reciprocating designs. Operation with vacuum inlet may benefit the regeneration process, but has negative effects on turbo compressor sizing and cost.

Does it make any sense?

The US DOE FECM Leadership Team message (the "Disclaimer" above) suggesting a Strategic Vision focus beyond 2050 ***seems to ignore near term potential*** for deploying CCS at existing (and new) power generating plants.

Modern high-efficiency gas turbine combined cycle (GTCC) plants could easily still be in operation past 2050. Why then isn't deployment of large post-combustion CCS at the source of power sector emissions a key part of the DOE Strategic Vision? Does it make any sense to count on ***future*** negative emissions based on DAC and capturing CO_2 at 0.04% (400 ppmv) concentration from the atmosphere vs. capture at 4.0% (40,000 ppmv) concentration from gas turbine exhaust with ***proven technology*** and at a ***fraction of the cost, now***?

The US Clean Power Plan (CPP) of 2015 established that 1000 lb CO_2/MWh, was "clean enough", allowing unabated gas plants to be permitted, while requiring coal-fired plants to add at least partial CO_2 capture.

The CPP and the EPA regulations accepted unabated gas-fired GTCC technology as satisfying the "best system emission reduction" (BSER) criteria under the existing Clean Air Act, and, therefore, required no further emission reduction measures to be applied.

To complicate matters further, and to effectively shut down any near-term prospect of requiring CCS for GTCC plants, the US Supreme Court recently ruled that under existing legislation the EPA lacks the authority to set standards for greenhouse gas emissions deemed to force a "generation switch", i.e., from coal to gas, or gas to renewables, by imposing standards too difficult to meet at reasonable costs.

The DOE also seems to put their "thumb on the scale" for DAC, with changes in qualifying facility size to encourage small installations and almost quadrupling the financial incentives.

As usually happens with big government spending involved, the most vocal advocates seem to have vested interests in DAC success. This hyping of DAC brings back memories of the days when sales of "beach-front vacation timeshare condos" were proliferating.

"Betting the farm" on DAC is just kicking the can down the road. Capturing CO_2 from the atmosphere, via a process having a 2nd Law efficiency of 7.8%, and at least 2-3 times the cost-of-capture with an inordinate and unsustainable energy input requirement fits my definition of ***"Chasing our Tail!"*** ■