CHEVRON'S FIG LEAF
A CASE STUDY OF CARBON ENGINEERING'S DIRECT AIR CAPTURE PLAN

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—

Mark Z. Jacobson, Stanford

Table of contents

Table of contents

Preface

— **Mark Z. Jacobson** —

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April 30, 2019

Global warming, air pollution mortality, and energy security are enormous problems that require immediate, rapid, and efficient solution. Given the limited funding available worldwide to solve these problems, it is essential that those funds be spent carefully and effectively. This report examines whether funding the direct removal of carbon dioxide from the air is an effective way to solve these problems.

The conclusion is, no. Instead, funding direct air capture (DAC) is an opportunity cost because spending the same money on clean, renewable electricity, such as wind and solar, is far more effective at solving all three problems. Wind and solar replace fossil fuel power plants, eliminating not only their carbon emissions, but also their air pollution emissions and their upstream mining, transporting, and fuel processing operations. DAC removes only carbon, and only partially, and at a much higher cost than renewables.

In fact, unlike clean renewables, DAC does nothing to reduce the 4 to 9 million air pollution deaths that occur each year worldwide. It does nothing to reduce the 50,000 new oil and gas wells drilled each year in the United States alone. It does nothing to eliminate coal trains, pipelines, oil tanker spills, gas explosions, or oil fires. It does nothing to reduce international conflicts over fuels. In fact, these problems worsen with DAC because more energy is needed than without DAC to build, run, and provide energy for the DAC equipment.

Further, a large portion of the carbon that is captured is returned to the air due to the additional energy needed. The carbon that is captured has limited uses on a large scale. Its major use today is enhanced oil recovery, and another option is to produce other combustion fuels that continue the air pollution problems of fossil fuels. From a social cost perspective, even if DAC were free, purchasing a wind turbine or solar panel would cost society less than would DAC.

This report takes us through several of these issues in detail. The report is eye opening and should be heeded by policy makers considering the different options for addressing the major problems we face.

1.

Executive Summary

The IPCC's Global Warming of 1.5ºC report features carbon capture in 3 of its 4 scenarios, but global investment in actual carbon capture plans is limited compared to the scale of the challenge. Chevron, BHP and Occidental recently invested a substantial portion of $68 million, roughly 1% of the global carbon capture expenditure of the past decade, into a single company in a small town in British Columbia. It's worth assessing Carbon Engineering further.

Carbon Engineering has built a carbon direct-air-capture proof of concept. Direct-air-capture's promise is to reduce CO_2 in the atmosphere by mechanical means. Its reality is that it's orders of magnitude too small for the scale of the problem, is incredibly expensive and that there's no useful market for the captured CO_2.

Carbon Engineering's solution produces 0.73 tons of CO_2 from natural gas for every ton of CO_2 it captures from the atmosphere. The only market for their solution is enhanced oil recovery which negates any benefits.

Its promised air-to-fuel approach would lead to a fossil fuel substitute or additive that would be in the range of 25 times the cost and 35 times the CO_2 emissions than just using electricity in electric vehicles. If the money had been spent on renewable generation instead, they could drive electric cars 130 times as far with much lower CO_2 emissions.

Carbon Engineering's solution produces 0.73 tons of CO_2 from natural gas for every ton of CO_2 it captures from the atmosphere.

The first rule of being deep in a hole is to stop digging. It's not like the jury is out on this, except for people like David Keith and Chevron. Experts such as Dr. Mark Z. Jacobson of Stanford and Dr. Sgouris Sgouridis at Khalifa University in Abu Dhabi agree that there is no warming world in which burning natural gas to capture carbon from the air makes sense, both asserting that building renewable generation instead is rational.

Chevron, BHP and Occidental have purchased a PR fig leaf which might incidentally allow them to pump more oil from played out oil fields.

2.
Context

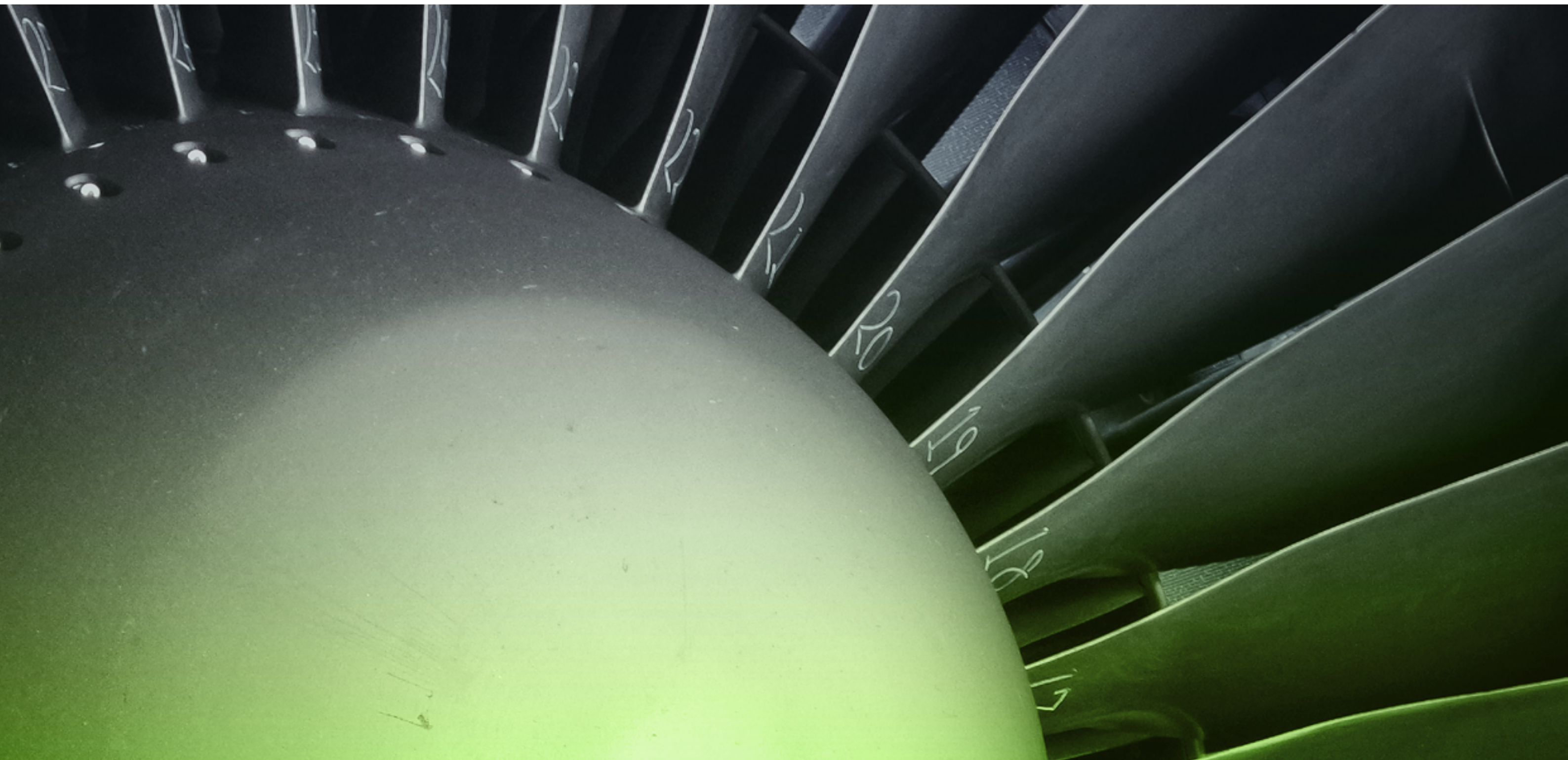
Recently headlines announced a $68 million dollar investment in a company that is building air-carbon capture technology. Headlines claimed it could scoop CO_2 from the air we breath economically. Hyperbole, like 'magic bullet', was spread liberally around. The threshold number of $100 per ton of CO_2 was bandied about.

This of course leads to the requirement for assessment. After all, $68 million looks like a lot of money. Magic bullets don't grow on trees. CO_2 is spread extremely thinly through the atmosphere. And what exactly are those multi-billion dollar companies getting for their money?

The total CO_2 load for the energy required for capture, processing, compression, storage, distribution and sequestration is almost certain to be greater than the CO_2 removed from the atmosphere.

The magic bullet in question is an air-carbon capture solution from a company called Carbon Engineering. It's based in Squamish, BC and just received $68 million in funding, a large portion of it from three fossil fuel majors. One of the company's principals is a seriously intelligent engineer who accepts the science of global warming, but likes geoengineering, burns fossil fuels to capture CO_2 from the atmosphere, and doesn't like wind generation.

Carbon Engineering's solution burns natural gas sufficient to create half a ton of CO_2 in order to capture a single ton of CO_2 from the air. They assert that they capture about 90% of the natural gas upstream and in-process CO_2 emissions. They actually have three separate CO_2 extraction technologies running in order to just take CO_2 from the air with one of them. The technology won't scale to anywhere near the size of the problem. The only potential use case for it is enhanced oil recovery, pulling more carbon from underground in tapped out oil wells.



At the heart of its technology is a clever re-use of existing technology, contactors. Like sorbents, another technology used in air carbon capture, a contactor is a filter for atmospheric CO_2. It has a honeycomb of material that is wetted with a solution which captures CO_2. The CO_2 is then precipitated out of the solution into a solid, which is then baked at 900 degrees Celsius to capture the CO_2.

To scale to a million tons of CO_2 a year, the company would need 2,000 two-meter fans blowing air into contactors in an array 20 meters high, 8 meters thick, and two kilometers long (broken up into 10 slabs) surrounding a central gas-fired CO_2-processing plant which also generates the electricity for the fans in the primary model. The company currently has a single fan working with a portion of its solution and isn't achieving the efficiencies required for its goals, although it has an explanation for that. As the problem is gigatonnes of CO_2, the company is four orders of magnitude off of a real solution, and the price tag to make this type of technology absorb useful amounts of CO_2 would be in the trillions annually.

Professor Mark Z. Jacobson of Stanford provided some insight based on his review of the Carbon Engineering technology.

SDACCS (synthetic direct air carbon capture and storage) is not recommended in a 100% renewable energy world. SDACCS is basically a cost, or tax, added to the cost of fossil fuel generation, so it raises the cost of using fossil fuels while reducing no air pollution and providing no energy security. To the contrary, it permits the fossil fuel industry to expand its devastation of the environment and human health by allowing mining and air pollution to continue at an even higher cost to consumers than with no carbon capture.

3.

Bottom-up Workup

For the sake of this assessment, let's do a bottom-up assessment of likely energy needs and potential energy supplies and CO_2 implications, and then contrast it to Carbon Engineering's technology and claims per its published papers in academic journals. The contrast will be illuminating.

The headline of one of those assessments I published, triggered in part by a previous glowing article about Carbon Engineering, is *Air Carbon Capture's Scale Problem: 1.1 Astrodomes For A Ton Of CO_2.* You have to push a lot of air through a small and resistant space for absurd amounts of time to get a ton of CO_2 with a perfect capture method. I estimated that with close to 100% efficiency and several other conservative assumptions, it would take about 0.044 MWh just for moving the air to capture 1 ton of CO_2. This used standard 1-meter diameter industrial fans, not the most efficient choice, but the specifications were at hand. I excluded back pressure, heating, cooling, movement of physical components, and the like.

For much of this assessment, I'll posit a device which captures a ton of CO_2 an hour, then later extrapolate to a million tons a year of capture, which is Carbon Engineering's reported per plant target.

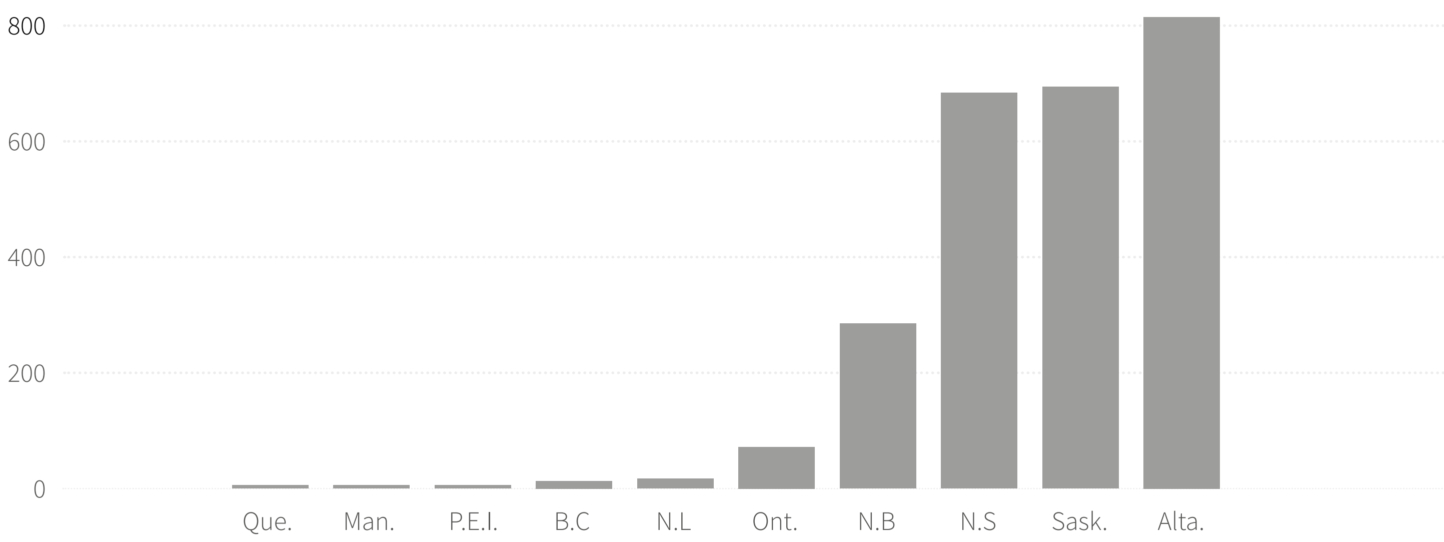
In addition to the large job of just moving sufficient air, Carbon Engineering's technology has another major energy concern, the 900 degree Celsius heating process which bakes the CO_2 out of the precipitate. Let's consider that a more reasonable number with a minimum air flow through the contactor technology, a processing cycle, a cleaning cycle, and then pressurization and storage. That is probably in the range of 4.4 MWh of electricity for a ton of CO_2.

Carbon Engineering is in Squamish, BC just north of Vancouver

Let's model this out with electricity as the primary energy source to start, as it seems eminently sensible to use a primary energy source which can be carbon-neutral itself to extract CO_2 from the air.

What's the carbon load of 4.4 MWh of electricity? Carbon Engineering is based in BC, which has a lot of hydro, and as a result, very low grams of CO_2e per kWh : 15.1 grams CO_2e / kWh.

Electricity Production GHG Emission Intensity, 2013 – CO_2 emission [g/kWh]



Source: Environment and Climate Change Canada; The Conference Board of Canada.

That doesn't seem like a lot, but there are 4,400 kWh in 4.4 MWh. A little math and it's apparent that in order to capture the ton of CO_2, you end up with electricity that emits about 66 kilograms. If Carbon Engineering were using electricity as the primary energy source and the demand were 4.4 MWh, this would be reasonable.

What does 4.4 MWh of electricity cost in BC? It's running ~6 cents CAD per kWh for large customers and Carbon Engineering would definitely qualify if it were using electricity. At BC rates, 4.4 MWh would cost about $265 CAD or $200 USD. Running it for a year with 5% maintenance downtime would be an electricity cost of about $2.1 million CAD or about $1.6 million USD, and **would only capture 8,300 tons.**

Carbon Engineering is claiming $100 per ton USD according to the BBC article, or about $133 per ton CAD. That's a big gap from $265. That means that its claimed process would only consume about 2.2 MWh per ton of CO_2 if the company was running it off electricity as a primary energy source.

Could it really be 50% cheaper? Well, it's hard to see how. And Carbon Engineering doesn't actually claim that in its underlying peer-reviewed publication. The paper that triggered the latest round of headlines was published in Joule, a brand new cross-disciplinary journal focusing on energy at all scales, which has no impact factor yet. (Yes, the lack of an impact factor and the vagueness of Joule's mandate is a red flag, implying challenges with getting the right peer reviewers on submissions. A bit more on this later.)

Here's what is actually said in that paper (dollars in USD):

Levelized costs of $94 to $232 per ton CO_2 *from the atmosphere.*

Well, that's not $100 per ton. The company has just built its first prototype and its current range barely includes the claimed $100. In Canadian dollars, it's $125 – $310 per ton, nicely bracketing the bottoms-up electricity-only model of $265 CAD. Okay, we have some hyperbole from the press and a paper published in a brand new and weak (so far at least) journal which is more realistic. But the bottoms-up numbers are in the ballpark and probably more realistic than the $100 claim.

The paper also claims moving the air only takes 61 kWh per ton of CO2. My modeling with lower scale fans (hence less effective and efficient) suggested 44 kWh per ton of CO2 without back pressure. That's in the ballpark.

What if Carbon Engineering set up right next door in Alberta and ran this off electricity from the grid? Well, Alberta's electricity is at 820 grams of CO_2e per kWh. That's over 50 times worse than BC. The required 4.4 MWh of electricity would produce 3.6 tons of CO_2e to capture one ton of CO_2e. And the bottom end of 2.2 MWh? That's still 1.8 tons of CO_2e emissions. Even at its own claimed energy intensity, in Alberta the company would be significant net emitters.

4.

Carbon Engineering's Solution

Capturing carbon from the air requires energy. Working it up using electricity showed that in BC it would be okay, but it would be deep underwater in Alberta. But how is the company actually powering their process?

When CO_2 is delivered at 15 MPa, the design requires either 8.81 GJ of natural gas, or 5.25 GJ of gas and 366 kWhr of electricity, per ton of CO_2 captured.

That's interesting in a couple of ways. First off, how does the actual energy consumption compared to our bottoms-up modeled consumption? They need 8.81 gigajoules per ton of CO_2 and 3.6 GJ is equal to 1 MWh. The company is asserting a total energy demand in the range of 2.4 MWh per ton of CO_2. And with its 61 kWh for air movement, Carbon Engineering is using around 75% of its energy to get the CO_2 out of its solution after it is captured.

For contrast, the average BC residential natural gas consumer uses about 125 GJ per year, so the gas for heating a home and cooking for a year could capture about 14 tons of CO_2. Put another way, the natural gas required to capture a million tons of CO_2 could provide heating and cooking for over 70,000 households in BC. That's about 4% of the households in that Canadian province.

Each GJ of natural gas is about 27 cubic meters, so getting a ton of CO_2 would burn about 240 cubic meters of natural gas. Each cubic meter weighs about 0.7 kg, so that's just under 0.2 tons of natural gas to get a ton of CO_2. That's a new demand driver for natural gas, it seems.

If Carbon Engineering is burning natural gas for energy, then it creates CO_2 as well. The Joule paper indicates that for every million tons of CO_2 it captures from the atmosphere, the company also captures about 500 thousand tons from the natural gas it is burning with no grid electricity.

Its process boils down to capturing a ton of CO_2 from the air by creating half a ton of CO_2 from fossil fuels.

That would great if it could be carbon neutral even powered by natural gas. It would just take the technology to approach 100% effective at removing CO_2 from a source volume of gas. But is it at 100%? Once again, per the Joule paper on its actual results with its prototype:

At an inlet velocity of 1.4 m/s the contactor ingests air at 180 t/hr, yielding a 45 kg-CO_2/hr maximum capture rate at 42% capture fraction.

The prototype is only capturing

– 42% –

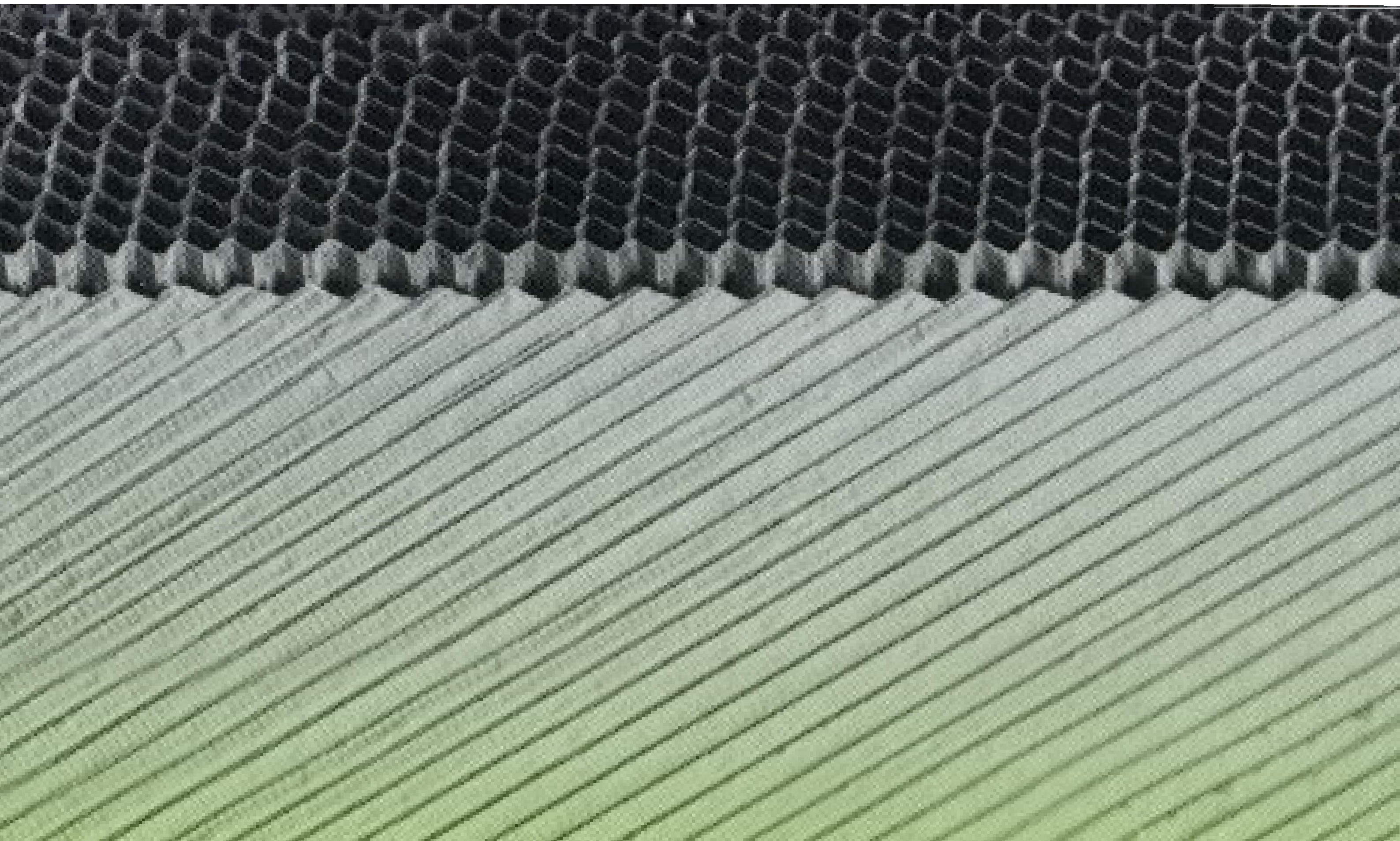
of the CO_2 from the atmosphere

What that translates into is that its prototype is only capturing 42% of the CO_2 from the atmosphere passing through it.

That's only for the air that's being pulled through the contactor. The company makes a much higher claim in the predecessor paper to the recent Joule piece, 75% under optimal conditions. That paper was published in 2012 in the journal The Philosophical Transactions of the Royal Society, which has been around a long time and does have an impact factor. The claim in 2012 was $60 per ton of CO_2 USD rather than the 57% higher $94 it claims as its current bottom end, never mind its 250% higher current top end of $232.

There's a bit of a glitch in the matrix here. Per the Joule paper which estimates $94-$232, Carbon Engineering is using 74.75% as its capture fraction, despite only achieving 42% with its prototype unit. The company asserts: "performance model validated by pilot data," but that's not well explained.

Brentwood structured packing used by Carbon Engineering



The contactor is basically a bunch of honeycombed material with a solution that captures CO_2 dripping through it. Carbon Engineering asserts that the prototype uses only 3 meters of Brentwood structured packing as opposed to ~8 meters in the production design (per my understanding), which would explain at least some of the capture fraction difference, but I was unable to find the specific calculation in its Joule paper to justify 74.75% (which may be my reading, not their paper).

It's also unclear if the company has modeled the significantly increased back pressure from 8 meters vs 3 meters for air movement. I'm more uncertain about its air movement numbers having looked into this than I once was, as I wasn't able to find a justification for the 61 kWh (once again, this could be my reading, not their papers). One good thing that the company is doing is using off-the-shelf commoditized components, albeit in a novel way, so it should have good metrics on this.

Complexity is increasing. With increased complexity comes increased cost and diminished efficiency.

For the emissions from the natural gas, the company is going to bolt on a completely separate pair of carbon capture technologies which operate at a claimed 97.5%. The further claim is that with the upstream emissions of natural gas, it is at about 90% efficiency in terms of captured CO_2 to emitted CO_2. That's not bad if true. But it is still creating 50% more CO_2 from fossil fuels as it captures CO_2 from the air. That CO_2 could just be left in the ground as an alternative solution, and as Mark Jacobson pointed out, all of that natural gas has negative externalities unrelated to CO_2 which are not captured.

For the emissions from the natural gas, the company is going to bolt on a completely separate pair of carbon capture technologies which operate at a claimed 97.5%.

Expanding on this a bit, the company is targeting 1 million tons of air CO_2 capture per year per plant. Each ton includes a net loss of 10% of the CO_2e emissions inherent in its fuel, that is, a ton of captured CO_2 has a 0.1 ton emissions tax. A million tons means that it is committing to production of 100,000 tons of uncaptured CO_2 from using natural gas in order to get a million tons of CO_2 from the air. If it didn't do anything and taking its numbers at face value, it would achieve 100,000 tons of CO_2 not emitted for zero cost compared to a million net tons sequestered for $94 million to $232 million. Which has the best cost benefit ratio?

As a note, it also requires 4.7 tons of water for every ton of CO_2, most of which is reused. A lot of the energy consumption goes to heating that water to create steam required as part of the process. Very heat intensive, which is why the company needs the waste heat and energy of burned natural gas to power its process.

5.

Direct-air-capture's scale problem

All the air in the Grand Canyon only contains

– 1,270 –

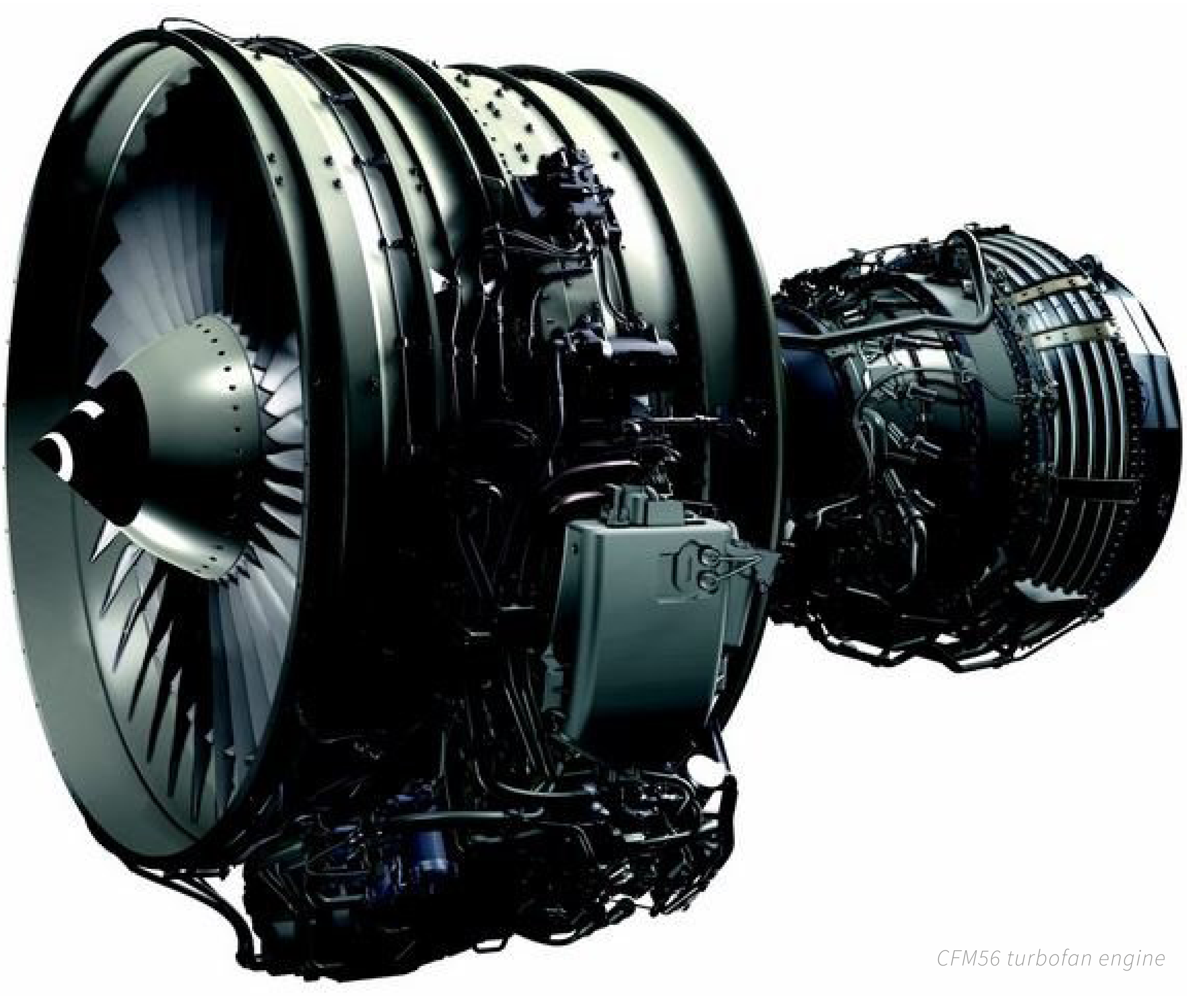
tons of CO_2

Grand Canyons's volume
is **1.67** billion cubic meters

The workup in the first sections focused on what it would take to get a ton of CO_2 an hour, or 8,300 tons in a year. But Carbon Engineering is thinking bigger, a million tons of CO_2 per year per plant, not 8,300. That's a factor of 120. The bottoms-up assessment modeled 44 ~1 meter diameter fans to get 8,300 tons without back pressure with a total surface area of about 90 square meters probably covering about 14 meters long and 5 meters high.

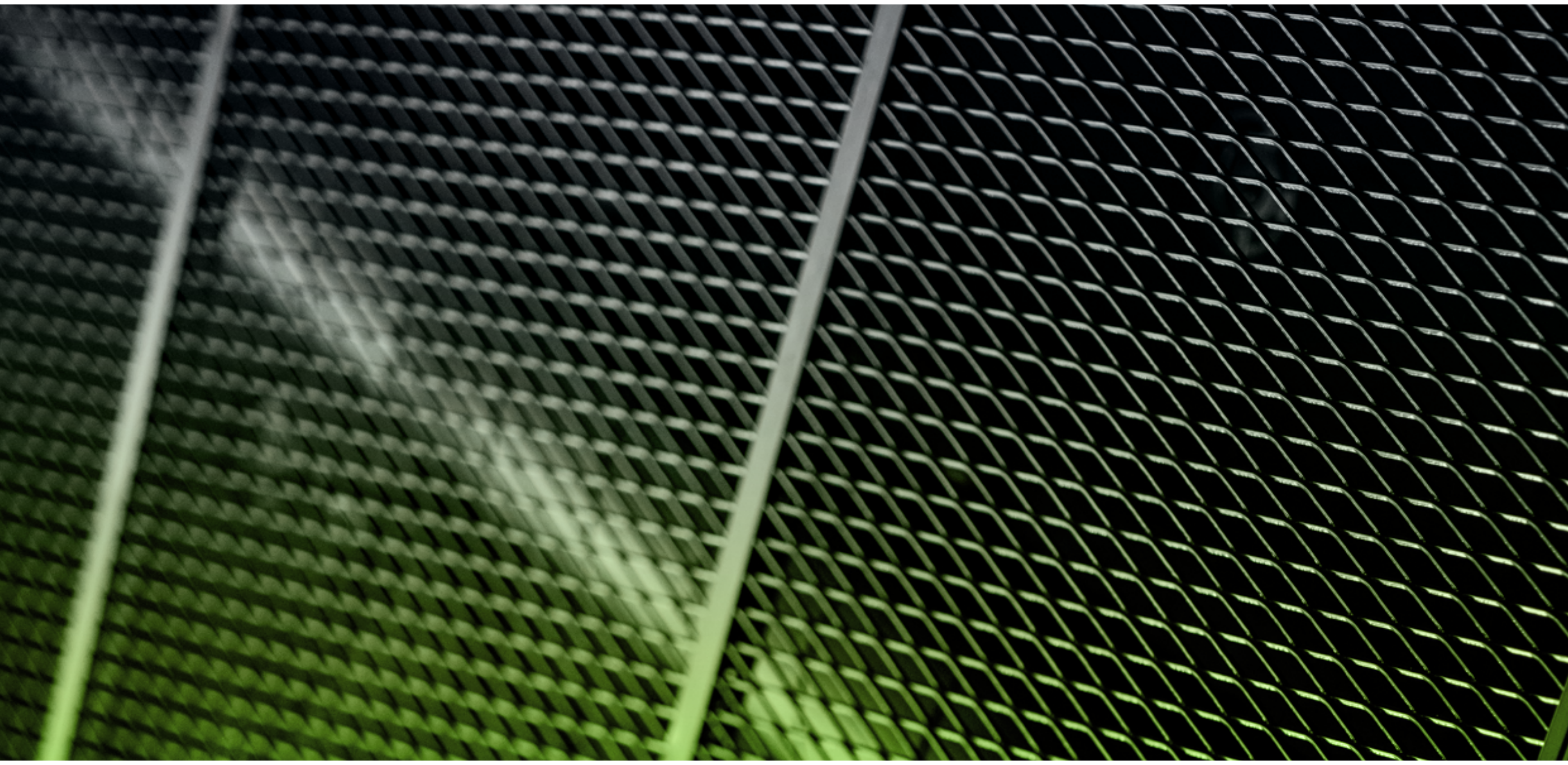
Given back pressure, let's assume a realistic number is 88 fans. That would be probably 28 meters long by 5 meters high simply because of engineering and wind load, etc. Then multiply by 120 to get over 10,000 fans. The 1-meter industrial fans cost about $500 a piece in bulk, so that's $50 million as a top end number. The surface area would be around 10,000 square meters of fans alone. Assuming its numbers and BC grid prices, that would be about $100 million CAD or $75 million USD in electricity per year.

There are, of course, much more efficient air-moving technologies when you get up to this scale, so one assumes we wouldn't need something that big, but still, it's going to be an enormous volume of moving air. Let's look at that for a minute. Getting a ton of CO_2 requires moving 1.3 million cubic meters of air at 411 ppm. That means that to get a million tons of CO_2 you have to move 1.3 trillion cubic meters of air.



CFM56 turbofan engine

A big passenger jet engine like the ones in the Airbus A340 moves about 0.465 tons of air per second and each cubic meter of air weighs about 1.2 kg. If you used a big jet engine, you could move all of the required air in about 100 years. That means you would need about 100 jet engines operating day and night for a year to get a million tons of CO_2. They're about 2 meters across with a surface area 4 times the size of the modeled 1-meter fans, so you'd have a 20-meter by 20-meter howling maw of noise and flame. Also it would be burning hydrocarbons, so why bother doing air carbon capture again? Illustrative of scale, but not a solution anyone is suggesting.



The image is a Carbon Engineering render of its contactor array. A lot of liquid solution flows in the top and gravity trickles it down through the packing and blowing air where it captures the actual 42% to the claimed potential 75% of the CO_2, then carries it into the processing system that retrieves it. The fans are about 4 meters in diameter. Its diagram stacks them four high with some additional space on the bottom to reach roughly 20 meters or 65 ft high. With slower moving fans, there are a lot more of them than the jet engine at a quarter of the surface area, but fewer than the basic industrial fan at a 16th of surface area.

It's pretty reasonable to assume that the fans aren't going to be pushing a quarter of the volume of the jet engine. Going back to bottoms-up estimates to help assess Carbon Engineering's claims, let's call it 10% per fan so instead of a 100 jet engines, you'd need 1,000 of the 4-meter fans. Stacked four high, that's 250 fans or a full kilometer wide. It's not really viable given the design and the need for air flow to buttress it allowing it to be a lot taller.

But if you want these things in stacked rows, say four of them, you'd need to space them out a lot or the ones further back will be sucking the

CO_2 light air from the ones in front. Probably 100 meters is more than enough, maybe less. Call it a 400-meter by 250-meter howling field of huge fans. And as a note, the company includes the point about spacing clearly in its papers. There is little evidence of basic engineering incompetence in the published papers, although I'm still skeptical of the air movement energy and the fraction capture of 74.75%.

Its earlier paper in the Royal Society journal bears out the bottom-up approach.

The engineering study described in §2b arrived at an optimized air-contactor design that is roughly 20 m tall, 8 m deep and 200 m long. In CE's full-scale facility design, roughly 10 contacting units would be dispersed around a central regeneration, compression and processing facility, to cumulatively capture 1 Mt yr−1.

It turns out the bottoms-up was off by a factor of two. The company would need 2 kilometers worth of its slab construction which implies that it is getting 5% of the jet engine's air through each 4-meter fan per unit of time. Remember that this only gets a million tons a year when the problem is in the gigatons per year, 4 orders of magnitude off of the scale of concern. Imagine 10,000 of these clusters of arrays of contactors with all fans running 24/7/365.

It's going to be a very noisy neighbor. No one will be able to live within a mile of this beast even with noise shrouding tech. You can make it quieter by making it slower or spreading it out more, but there are absurdities involved in this process.

But that's only capture and storage. Moving tons and tons of CO_2 after it's captured takes energy. Sequestering it or turning it into something else takes energy. There's no real win here.

There are ways to reduce this. One is to use waste industrial heat for a portion of the energy problem. Global Thermostat's model works that way. The principals of that firm, Graciela Chichilnisky and Peter Eisenberger, realized early that in order for air carbon capture to be used, it had to deal with the heat issue carefully. The Carbon Engineering team, as we discovered, just decided to burn lots of natural gas.

Another is to do the air carbon capture at the place where it's needed or will be sequestered. That gets rid of a lot of the distribution costs. Once again, that's Global Thermostat's business model. The company talks about the 400 square kilometers of greenhouses north of Beijing that all run on high CO_2 concentrations to optimize growing and have lots of waste heat to run through the system. They talk about concrete plants that have high heat and can use CO_2 as a feedstock with binding into the finished product and is sold. What Carbon Engineering is useful for is a rather different thing, which will be discussed later.

Another approach is to run an electrically powered air carbon capture solution off of a bunch of renewable energy that you build for the purpose. Imagine, if you will, a big solar farm with one of these plugged in on the side. Well, let's play that out, shall we? Let's assume that ton per hour, because that seems reasonable. Let's also assume the 4.4 MWh per ton. That requires 4 MW of capacity of solar to get a ton of CO_2 in an hour. This is also assuming accepting 'free' solar energy when it's available to run the process rather than running it full time. This means we get about a ton at peak sunlight, but less the rest of the day and none at night.

Well, that's approximately another $4.4 million in capital costs for the solar farm. You need about

7.6 acres per MW of capacity, so that's 33 acres or 13 hectares. You won't be building one of these in the city, that's for sure. How would it be near Squamish, where Carbon Engineering is located? About $100,000 per acre asking price for larger acreages per real estate sites? So another $3.3 million for the land, so you won't be building that near any cities. That's close to $8 million before you get to the device. And that only captures about 15–20% of what the machinery can do because that's the capacity factor for solar. That's not looking good.

Want a mixed wind, solar, and battery farm for 24/7/365 operation? That's in the range of $100 million capital costs for power production, storage, and management, and at that you'd be selling a lot of wind energy to the grid because it doesn't make sense to build a wind farm for only 4.4 MW peak demand, so you'd be building a 10 MW wind farm minimum. The batteries are the kicker. Tesla Gridpack is in the $70 million range by itself for three days if you want to stay off grid. Yes, battery storage is still expensive; thankfully storage is much less necessary on grids than people assume. You can probably scale back and find some workable model, but still, it's unlikely that anyone would power this low-value solution with purpose-built renewables.

If it were electrically powered, you could hang this thing off the near side of an offshore wind farm with an inadequate transmission pipeline to population centers so there's frequently some excess electrical generation capacity with no use for it. You could sop up some of the excess by doing air carbon capture and combining it with hydrogen electrolyzed from seawater to create a clean, synthetic biofuel. Of course, that's close to what some fossil fuel companies in Europe want to do with that situation, but they just want to make hydrogen and inject it into the gas lines for a 20% reduction in gas generation CO_2 emissions. That looks like a bigger win than air carbon capture, even though it's very wasteful of energy. You could just deliver that carbon-free electricity to useful demand areas and let it be used productively and displace a MW of coal or gas emissions instead.

> What are the CO_2e emissions of an efficient natural gas generator? About 500 grams of CO_2e per kWh.

Finally, you could use a combined heat and power natural gas generator to provide both the electricity for the fans and the heat. That could get you down to the 2.2 MWh number because you are using waste heat. But wait. What are the CO_2e emissions of an efficient natural gas generator? About 500 grams of CO_2e per kWh.

And that's where Carbon Engineering is. It is burning natural gas, producing 50% of the CO_2 from that that it is capturing from the air, and producing 150% of the CO_2 in the air without an observable market or business case.

6.

Air-to-fuel evaluation

The Canadian government funded Carbon Engineering for an air-to-fuel commercial scale plant, and Carbon Engineering's website and recent press tout their air-to-fuel process. However, there are no published papers or findings, merely claims. A deep dive specifically into air-to-fuel and what the results will be is required.

Air-to-Fuels Development, Feasibility, and pre-FEED Study for First Commercial-Scale Demonstration Plant

LEAD PROPONENT	**CARBON ENGINEERING LTD.**
LOCATION	**SQUAMISH, BC**
CEI CONTRIBUTION	**$ 2,250,000**
PROJECT TOTAL	**$ 7,893,609**
STRATEGIC AREA	**CARBON CAPTURE, USE AND STORAGE**

Source: official Canadian federal website and $7,893,609 CAD for Carbon Engineering

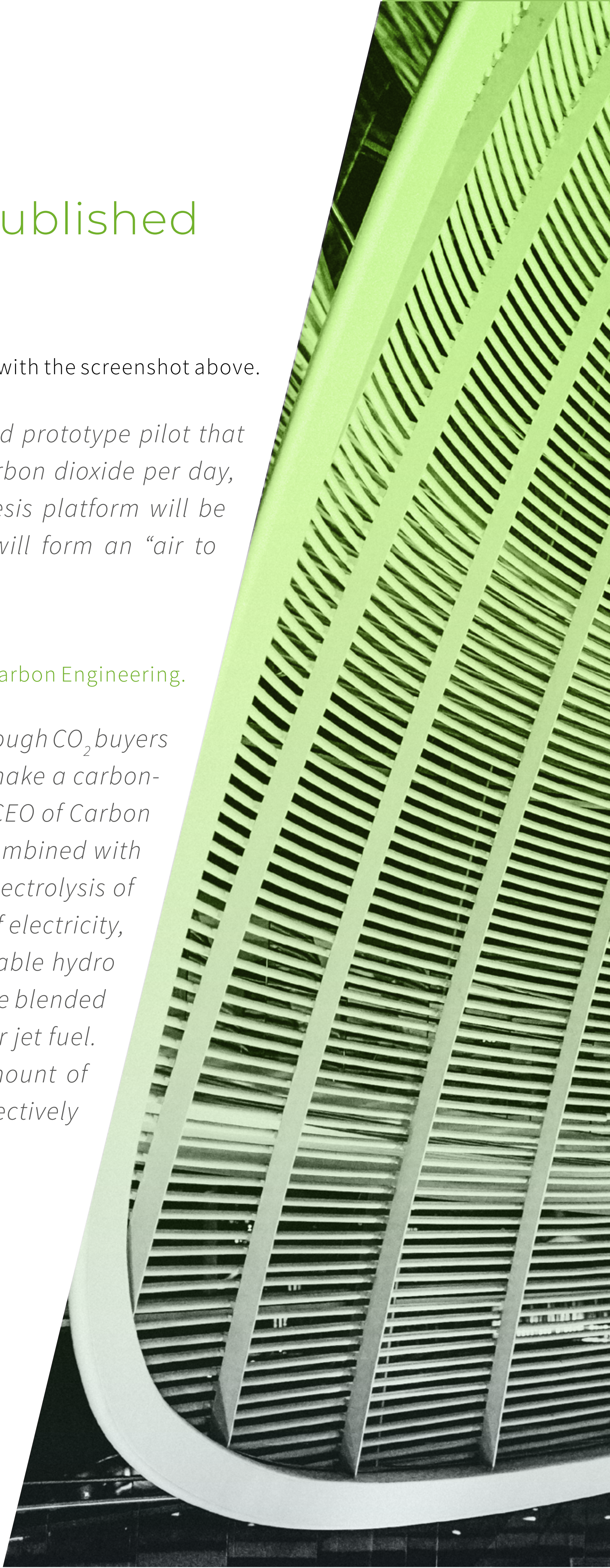
6.1. What are the published claims?

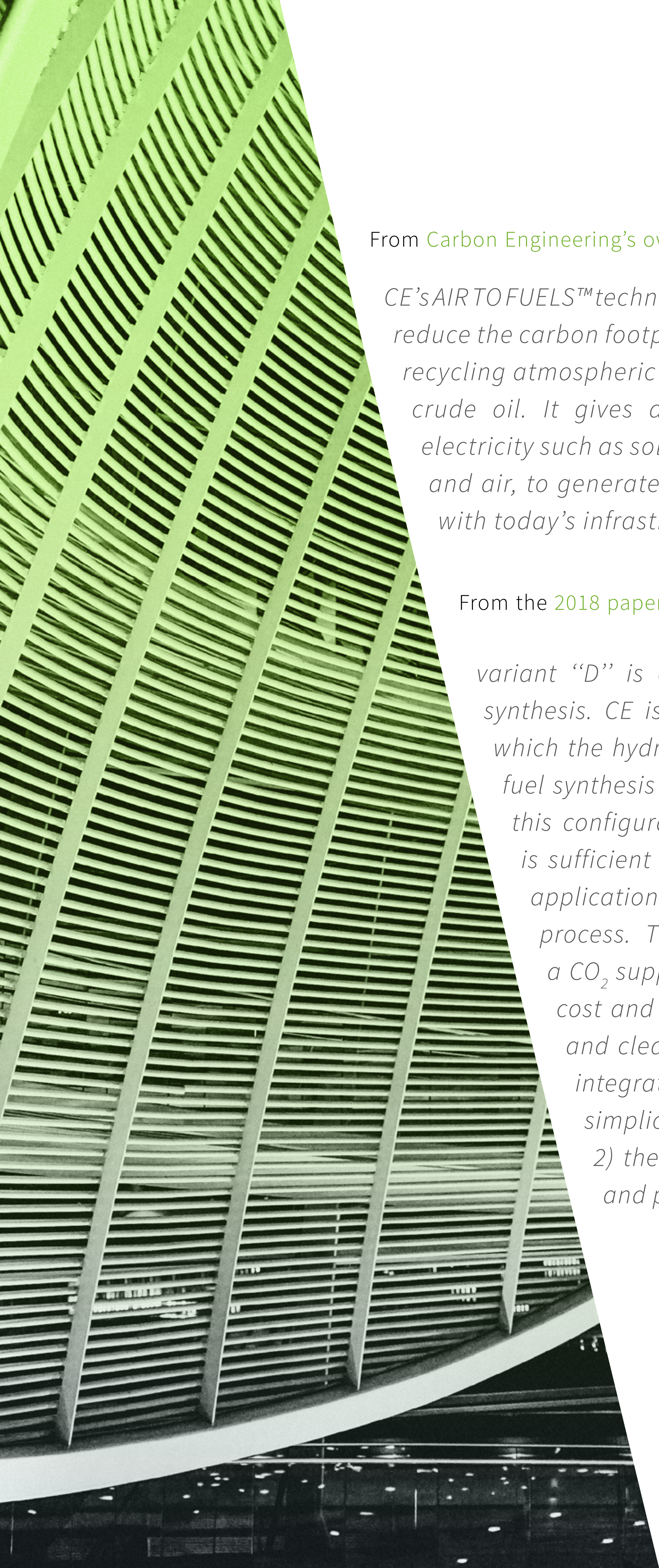
From the Canadian federal government page with the screenshot above.

Building on a successfully demonstrated prototype pilot that can capture 1 tonne of atmospheric carbon dioxide per day, a hydrogen production and fuel synthesis platform will be integrated into this prototype, which will form an "air to fuels" prototype system.

From a 2018 National Geographic profile on Carbon Engineering.

Still, even at $100 per ton, there aren't enough CO_2 buyers right now. So the company decided to make a carbon-neutral liquid fuel, said Steve Oldham, CEO of Carbon Engineering. […] The captured CO_2 is combined with hydrogen, which is made through the electrolysis of water. While the process requires a lot of electricity, the pilot plant in Squamish uses renewable hydro power. The resulting synthetic fuel can be blended or used on its own as gasoline, diesel, or jet fuel. When it's burned it emits the same amount of CO_2 that went into making it, so it's effectively carbon neutral.





From Carbon Engineering's own website.

CE's AIR TO FUELS™ technology provides a tool to significantly reduce the carbon footprint of the transportation sector by recycling atmospheric CO_2 into liquid fuel and displacing crude oil. It gives an ability to harness low-carbon electricity such as solar PV, and material inputs of water and air, to generate fuels that are drop-in compatible with today's infrastructure and engines.

From the 2018 paper:

variant "D" is optimized to provide CO_2 for fuel synthesis. CE is developing air-to-fuel systems in which the hydrogen required as feedstock for the fuel synthesis step is produced by electrolysis. In this configuration, the oxygen from electrolysis is sufficient to supply the DAC plant, so in this application we drop the ASU from the DAC process. The fuel synthesis system requires a CO_2 supply pressure of 3 MPa, reducing the cost and complexity of the CO_2 compression and clean up. CE is developing methods to integrate the DAC and fuel synthesis, but for simplicity of analysis, here we show (Table 2) the inputs for a plant that receives O_2 and produces atmospheric pressure CO_2.

6.2. What does this suggest?

As a reminder, the CO_2 that it was capturing in its primary process in both papers was one-third new CO_2 from natural gas, which had an upstream efficiency loss. This report was born as a 7-part series, and Dr. Mark Jacobson tweeted about in, pointing out that the actual efficiency was worse than I had asserted. The plant actually would emit almost 3/4 of a ton of new CO_2 for each ton actually captured from the air.


Mark Z. Jacobson
@mzjacobson
Following

Direct Air Capture Part II. Plant burns gas emitting 0.5 tons of CO2 for each ton of CO2 captured

cleantechnica.com/2019/04/13/che …
@cleantechnica @mbarnardca

In fact, after accounting for upstream CO2+CH4, this plant emits 0.73 tons-CO2 for each ton captured

web.stanford.edu/group/efmh/jac …

Chevron's Fig Leaf Part 2: Carbon Engineering Burns Gas For 0.5 Tons Of CO…
Carbon Engineering's solution is a natural gas hog that produces a half ton of new CO2 for each ton captured from the air.
cleantechnica.com

8:17 AM - 13 Apr 2019

41 Retweets 65 Likes

Of course, the company captures the CO_2 from burning the natural gas as well, ending up with 1.46 tons of pure CO_2 for every ton captured from the air in its primary process. If that were bonded into a liquid hydrocarbon and used as transportation fuel, that 0.73% is just emissions in the end. Assuming it produces 1.46 MTons per year and 0.48 Mtons of that comes from the natural gas, if it used solely gas for power and Jacobson's numbers are assumed to be correct, every ton of CO_2 it produced would be effectively 50% new CO_2 from the natural gas.

However, its 2018 paper has a purported optional configuration for air-to-fuel with a lower ratio. If I understand its Table 2, every ton of CO_2 captured from the air in its air-to-fuel configuration has 0.3

tons of CO_2 from natural gas added. Given upstream processing and the full carbon accounting, this suggests that we could use the ratio from its claimed 0.48 to Jacobson's 0.73. That gives a full carbon debt of 0.35 tons CO_2 from natural gas in every ton of CO_2 delivered. However, that might not account for the electricity which is very good in BC at 15.1 grams CO_2e / kWh. The CEO claim of clean hydropower is mostly accurate for BC as that is the primary grid generation source. The 77 kWh then turns into another 0.001 tons of CO_2, which is immaterial at this point and we can assume is included in Carbon Engineering's claimed 0.3 tons. It's interesting to read the new CEO saying that there were no big markets for CO_2, as this report points out later that the big market is pumping it underground to get more oil. That will be roughly a 0% improvement end-to-end when the resultant oil is burned.

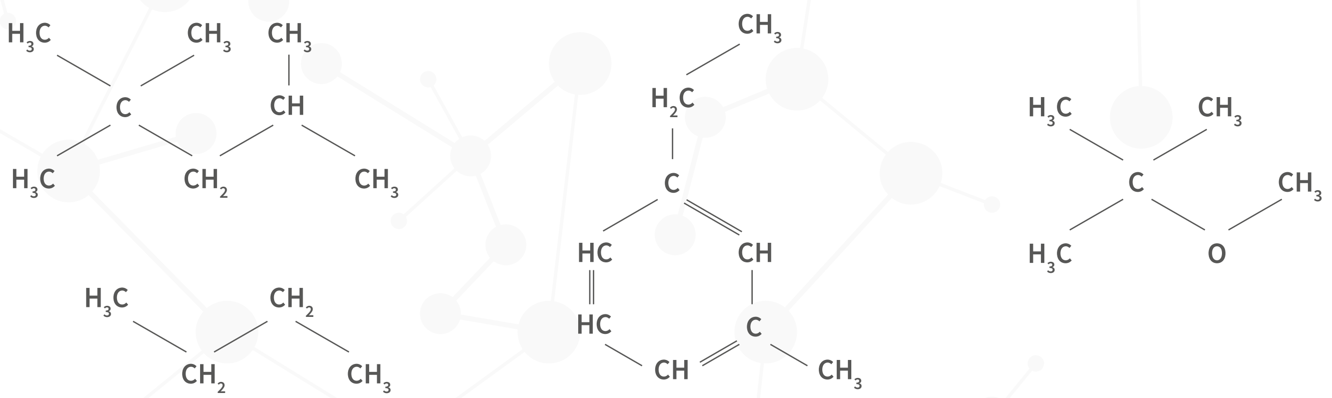
Lastly, the Canadian government's funding is disappointing. Apparently no one pointed to all of the various previous attempts from organizations which proved that this doesn't work economically, or did any of the rather basic assessments performed for this series, before handing over close to $8 million CAD (about $6 million USD). Not money well spent, redoing work previously done in a less carbon-neutral way. Especially when the fossil fuel majors were signing checks 10x the size.

6.3. Let's look at the technology

At heart all the company is doing is making a hydrocarbon fuel out of... umm... hydrogen and carbon atoms. It is going to make a 'carbon-neutral liquid fuel', per the statements, and has not published any clear statement about what it is making. It's not diesel or gasoline presumably, but a synthetic precursor or additive to fossil fuels with hydrogen and carbon that burn nicely.

Here's the thing about liquid fuels. Most of them aren't only hydrocarbons. The list of things you can make only with carbon and hydrogen — methane, ethane, ethene, ethyne, propane, propene — are notable by mostly being gaseous at room temperature and pressure, not liquids.

Let's take gasoline, abbreviated to gas and the source of much confusion in North America.



> *The bulk of typical gasoline consists of a homogeneous mixture of small, relatively lightweight hydrocarbons with between 4 and 12 carbon atoms per molecule (commonly referred to as C4–C12). It is a mixture of paraffins (alkanes), olefins (alkenes) and cycloalkanes (naphthenes).*

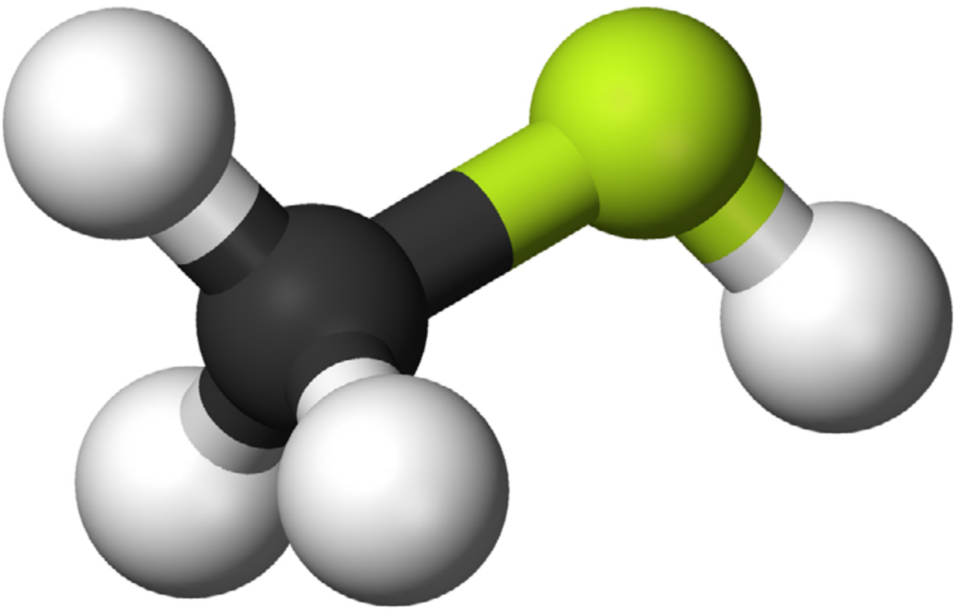
It's a chemical soup. One of the nice things about synthetic fuels is that they typically don't have anywhere the extraneous molecules naturally occurring hydrocarbons have, so you can make a cleaner burning fuel.

6.4. What might the company be making?

It is making a hydrocarbon, perhaps ethanol which has a chemical formula of C_2H_6O, is fairly easy to manage, and already works as a gasoline additive. The company might also be synthesizing butanol, which basically just has a lot more carbon and hydrogen atoms, or something else relatively simple.

The reference it called out from 1965 talked about synthesizing methanol, CH_3OH, using nuclear power. There are substantial downsides to methanol given toxicity and a global market of only 20 million tons, mostly controlled by Methanex out of Vancouver (more on this later). There are also existing methanol-to-fuel processes, as this has been tried many times before and found wanting. For the purposes of this analysis, we'll assume methanol, as it is the simplest and there's local expertise with methanol handling and shipping in BC.

Methanol model



There are many ways to create hydrocarbon-based liquids. As it is unstated and as Carbon Engineering has published exactly zero papers on liquid fuels or hydrogen creation that I was able to find, methanol is probably as good as any to use for the initial workup.

6.5. What is the energy & CO_2 cost of this?

I'm going to try tackle this a few ways. One way is a pure energy perspective. Another will try to assess carbon load. I'll figure out the cost of the resultant fuel for comparison as well.

We'll start with a ton of CO_2 with the alternative of 5.25 GJ of gas and 77 kWh of electricity, which the paper indicates is the air-to-fuel configuration. For the sake of comparisons as we go through, we'll convert the total energy into MWh for each component to do a build up and as we found earlier, 3.6 GJ is equal to 1 MWh. That means the CO_2 process for air-to-fuel has an equivalent of about 1.54 MWh. The paper's claim is O&M costs of $23 USD per ton of CO_2, with a levelized cost of $94-$130 USD per ton for this process. We'll use the $112 average for the cost workup.

6.6. How much hydrogen do we need?

Let's start with how many molecules of CO_2 there are in a ton. According to this source, it's 22,700 mol CO_2. As a reminder for people like me who don't do this every day, mol is short for mole which is $6.022\times10_{23}$ molecules of CO_2. It's easier to work in mols than in the result of moles times $6.022\times10_{23}$. But the weight of the C specifically is a lot lower. Carbon is only 12 grams of the 44 gram weight of a mole of CO_2. So the carbon is only about 272 kilograms of the ton of the CO_2.

Assuming a 100% efficient process (they never are), that means that we need 4 times as many hydrogen atoms as carbon atoms. That's 90,800 mol H, but hydrogen only comes in molecules, mostly H_2. We need 45,400 mol H_2 to combine with the 22,700 mol CO_2. Hydrogen is really light stuff with a molecular weight for H_2 of 2. Each atom is one-sixth the weight of carbon and one-44th of the mass of a single CO_2 molecule.

The easy way to figure out how much this weighs is to multiply 45,400 mol by 2 g/mol. Turns out you need 91 kilograms of hydrogen to add to the ton of CO_2. There's a process-efficiency catch in creating methanol, which is that you convert H_2 at relatively low efficiencies so you have to take multiple passes in most processes, leading to about a 95% final efficiency. So you actually need a bit more hydrogen, about 96 kg.

There are couple of major paths to get hydrogen out of water, and the company is vague on the specific electrolysis process it is using, but all are energy intensive. High-efficiency, high-volume PEM electrolysis sees about 80% efficiency and it takes about 50 kWh of electricity per kilogram of hydrogen. We need 96 kilograms of hydrogen, so that's 4.8 MWh of electricity. And at BC's very low 15.1 grams of CO_2e per kWh, that's another 0.07 tons of CO_2 emissions as debt for the hydrogen. In Alberta next door, as was pointed out in part 1, the 820 grams of CO_2e would mean that hydrogen from electrolysis would have a 3.9 ton CO_2e debt.

A 2014 PEM electrolytic hydrogen economic study clustered likely production costs — not retail price — around \$5 USD / kg H_2 for larger-scale facilities. That suggests that the hydrogen cost is about \$475 for the 95 kg.

After reviewing the initial series, Michael Desmond, PhD and co-author of the 2011 report *Direct Air Capture of CO_2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs*, pointed out that this rather devastating perspective on Carbon Engineering's approach is not devastating enough. The way the chemical processes for creating methanol, diesel, and kerosene work, water is also a product. As such, the hydrogen required is much higher. In the case of the diesel example, Desmond asserts that the input hydrogen is actually 0.137 tons, not 0.048 tons, suggesting that most of these examples are 2.74 times too low. Given that two separate credible sources are providing numbers at variance with one another, we'll stick to the one that's most beneficial to Carbon Engineering's solution as we have all along. As we'll see through the analysis, it doesn't matter now much benefit of the doubt we provide to the company's process, it's not viable.

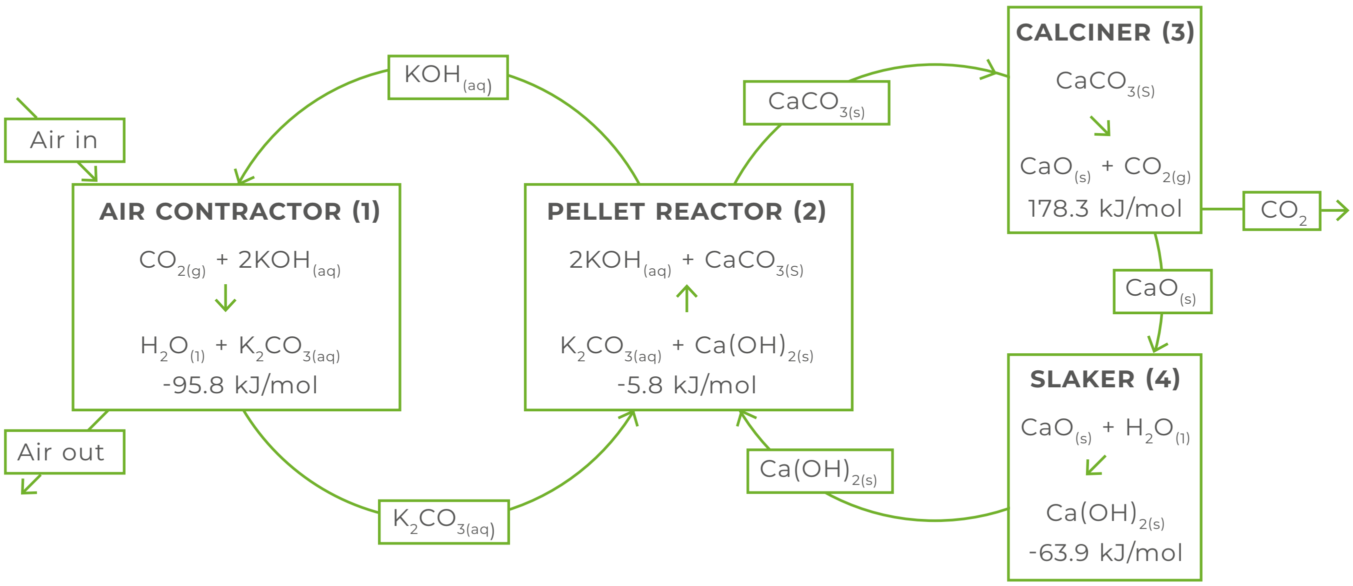
6.7. How much oxygen do we need?

How much oxygen do they need to bond with 272 kilograms of carbon to make methanol? CH_3OH is one carbon and one oxygen, so basically half of the remainder of the ton is the amount of needed oxygen. That's 364 kilograms.

Oxygen should be easy. There's a lot of oxygen already bonded to CO_2. The problem is that the carbon-to-oxygen ratio for CH_3OH is the different than CO_2. You have to break the bonds of an oxygen atom from every CO_2 molecule to get one of each for a methanol. However, its process assertion is that it receives pure O_2 from the hydrogen electrolysis process and will use that as its source. So over on the electrolysis side the company spends a bunch of energy to create hydrogen and oxygen, then in the CO_2 process it spends a lot of energy to bond it to carbon, then spend more energy to break the bonds leave CO_2, and then in the fuel synthesis cycle it spends a bunch of energy to break another chemical bond. Guess what, breaking up is hard to do. It requires energy to peel atoms off of stable molecules. Remember that creating CO_2 is normally exothermic, which means that you get it by burning carbon in the presence of oxygen, resulting in heat. Basic physical laws say it takes as much energy to break the bonds as you get when you form them, plus a little bit for entropy. Does this seem like it might be adding up to an odd energy balance?

It's likely worth looking in more detail at its process cycle to see if the company could use some intermediate molecule to get carbon without a lot of oxygen attached.

Process Chemistry and Thermodynamics



Well, no. The CO_2 is the result of stripping stuff off of $CaCO_3$ to leave CO_2 and CaO which is added back to the process. Going further back we see $K2CO_3$. Its process is already spending a lot of energy binding extra oxygen and then breaking it back out as part of the process of capturing it. There's no simpler feedstock from its model that I can see for methanol synthesis than the CO_2 output, and most of the literature on processes is CO_2 to methanol in any event.

The diagram above is only one of the chemical processes of course. The company also has a hydrogen electrolysis process, then you have to bind them together of course, and making liquid hydrocarbon fuels is creating exploitable chemical bonds by pumping energy into them.

6.8. How much energy to make methanol?

That's also well known, as people work on CO_2 to methanol processes all the time. There's a good 2016 study in Applied Energy, titled Methanol synthesis using captured CO_2 as raw material: Techno-economic and environmental assessment, looking at multiple plants producing thousands of tons a year, then an economic buildup. We'll pluck this out.

ENERGY BALANCE(MW h/t_{MeOH})

ELECTRICITY CONSUMPTION	**0.169**
HEATING NEEDS	**0.439**
COOLING NEEDS	**0.862**

Process energy needs for low-energy CO_2 + H_2 > methanol

So we need to turn our H_2 and CO_2 into methanol. The numbers above add up to 1.47 MWh, but we are only creating 0.73 tons of methanol, so that's another 1.1 MWh and has another CO_2 debt assuming BC electricity only, of 0.02 tons. Given the preference for heating using natural gas, the company may be using that instead, in which case the CO_2 debt would go up.

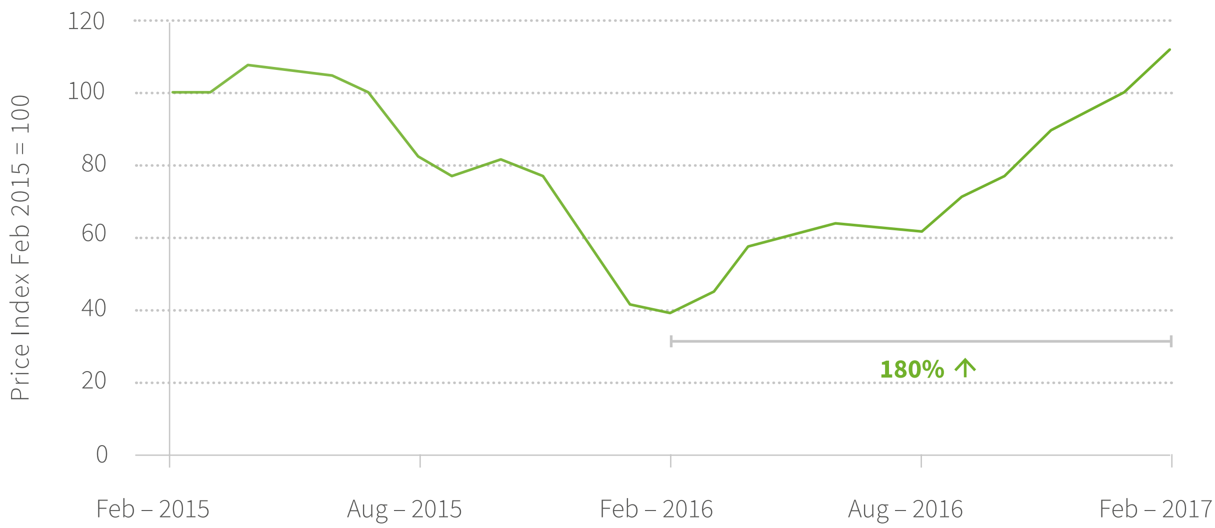
272 kilograms of carbon, 91 kilograms of hydrogen, and 364 kilograms of oxygen creates 727 kilograms of liquid fuel give or take a bit. In the end, its ton of CO_2 turns into about 0.73 tons of methanol.

6.9. What does energy & CO_2 look like so far?

PROCESS	TONS	MWh-e FOR PROCESS	CO_2 DEBT (TONS)	AVERAGE COST
CO_2	1.00	1.54	0.35	$112
HYDROGEN	0.10	4.80	0.07	$475
METHANOL	0.73	1.07	0.02	$329
TOTAL		**7.41**	**0.44**	**$916**

That's close to $1,000 USD per for the 0.73 tons of methanol, about $1,250 per ton. What's the market value of methanol? As a reminder, I mentioned that Methanex sets the global market for methanol. It's the 800-lb gorilla globally in this 20 million ton a year market. I happen to know this because I consulted briefly with the company and so learned about them. It's a boom and bust market with long periods of low costs and then periods of high demand, like the jump in 2017 by 180% to $500 USD per ton. Also as a reminder, a separate sources suggests that almost three times as much hydrogen is required as much of it bonds with the oxygen to make water.

Methanol Gulf Coast Benchmark Price



The chart is read as 2015 being the index price at 100%. So the best possible scenario for Carbon Engineering appears to be a price 2.5 times the historically high price of methanol. And the price in Feb 2016 was about $170 per ton, over 7 times cheaper. And no one was able to make methanol to gasoline work economically off of cheap methanol.

So right now, this is looking like it's economically non-viable, and we haven't even made it to the worst part yet.

6.10. How much energy is in 0.73 tons of methanol?

Methanol has an energy density of 20-22 megajoules (MJ) per kilogram. This means that the embodied energy in the 0.73 tons of methanol is 14.6 to 16.1 GJ or 4.1 to 4.5 MWh.

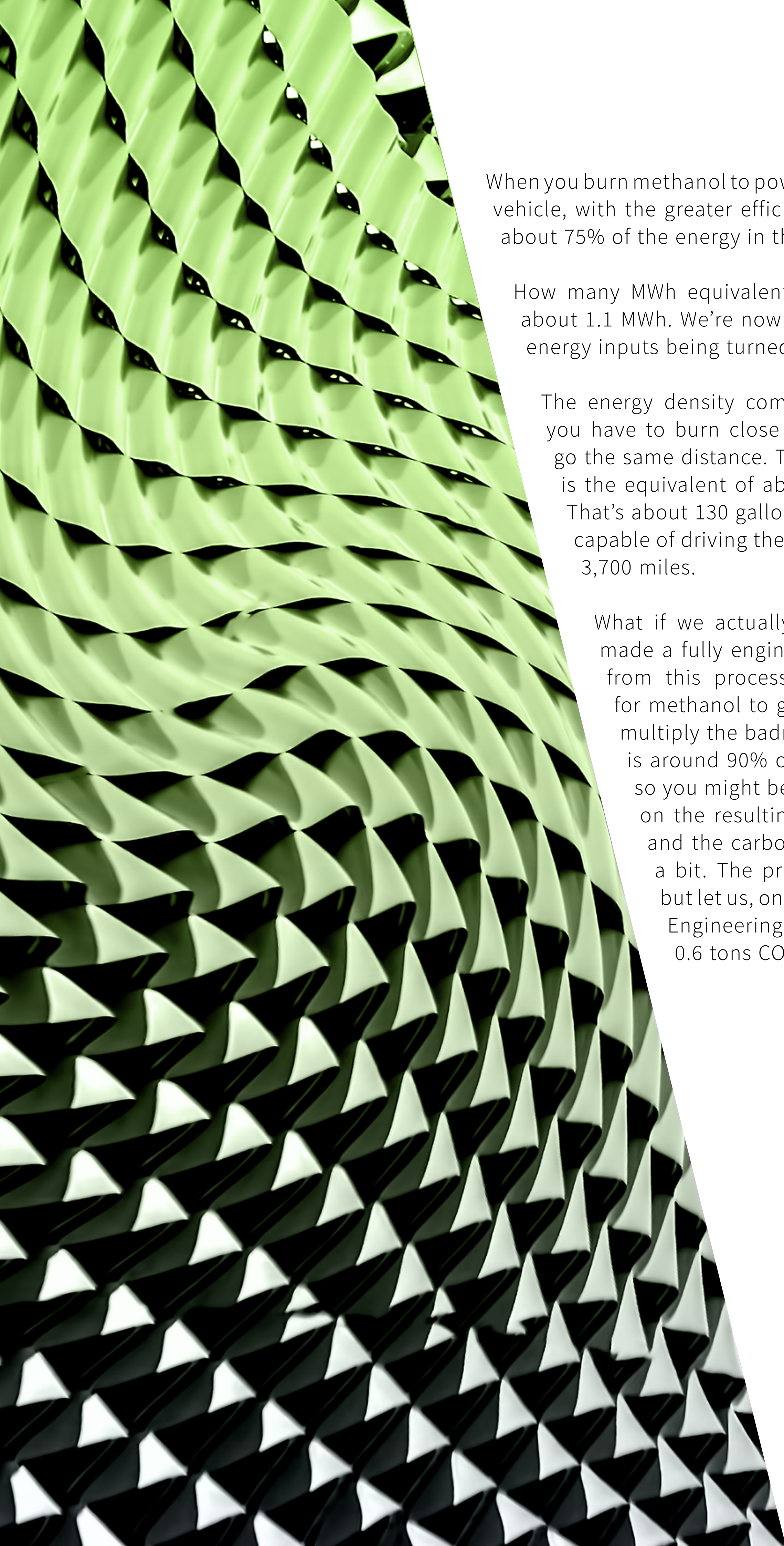
Wait. What's that? So far we've spent 7.4 MWh (without any distribution or further process costs) and we're only getting back 4.5 MWh equivalent energy? We've already lost 40% of the energy just for the chemical processes which create the useful fuel.

6.11. What about when it's used?

Let's go back to what the company's claim is, which is "to generate fuels that are drop-in compatible with today's infrastructure and engines." So that means not special engines, but today's engines. And its examples are all transportation. Let's do a little thought experiment.

Most car internal combustion engines average about 20% efficiency, meaning that 80% of the energy is wasted as heat. Toyota has a prototype internal combustion engine that hits 38%. Diesel are a bit better than basic gas engines at 30% or so. Jet engines vary drastically as well, but average for a big Boeing is around 36%.

Taking the car example, the simplest model is to add perhaps 10% of the methanol to gasoline to create a mixture that the car engine can run on. With adaptation you can run engines on pure methanol, and in fact some racing series do that. Methanol burns a bit more efficiently than gasoline but has only about half the energy per unit of mass. Blending is a very low energy process, but still you have to distribute the liquids, blend them, do process quality work, and store and distribute the result. Let's ignore that energy cost for now.



When you burn methanol to power an internal combustion vehicle, with the greater efficiency you still throw away about 75% of the energy in the liquid as heat.

How many MWh equivalent are we left with? That's about 1.1 MWh. We're now down to 15% of all of the energy inputs being turned into useful work.

The energy density compared to gasoline means you have to burn close to twice the methanol to go the same distance. That 0.73 tons of methanol is the equivalent of about 0.36 tons of gasoline. That's about 130 gallons or 500 liters of gasoline capable of driving the average 28 mpg car about 3,700 miles.

What if we actually took the final step and made a fully engine-compatible fuel for cars from this process? The process efficiency for methanol to gasoline is 50% to 60%, so multiply the badness by 2. Gasoline energy is around 90% of the methanol feedstock, so you might be able to travel 3,400 miles on the resulting of synthesized gasoline and the carbon debt would go up quite a bit. The process is pretty inefficient, but let us, once again, be nice to Carbon Engineering and suggest we're up to 0.6 tons CO_2 debt.

7.
What about diesel or jet fuel?

After the original series this report is based on was published, an independent energy researcher, Leon di Marco, challenged our assessment. He's spent a moderate amount of time publishing and talking about synthetic fuels, so we thought a follow-up was warranted.

If Carbon Engineering is making e-diesel, driving the same distance in a freight truck would cost at least 6.5 times as much and have 16 times the CO_2 emissions as just using electricity in a Tesla Semi.

Di Marco's assertion is that Carbon Engineering are using a Greyrock Energy Inc. patented process to transform CO_2 and hydrogen directly into a synthetic diesel or a synthetic jet fuel. Carbon Engineering has been silent on this, so we'll take di Marco at his word, plug in what we see and find out how Carbon Engineering's solution would stack up.

7.1. How does Carbon Engineering's freight diesel option stack up?

The Greyrock patent asserts that they have an effective process for creating a variety of heavy hydrocarbons depending on catalysts and process in a simpler approach than large scale refineries use. Diesel's average chemical formula is C_{12}H24. Comparing to methanol's CH_3OH, this potentially bodes well for Carbon Engineering as there are half the hydrogen atoms to carbon atoms required, 2:1 not 4:1. That means that given a ton of CO_2, we only need about 48 kg of hydrogen to add to the 272 kg of carbon (remembering the 5% hit on hydrogen that's lost to the process). That will save some money, energy and CO_2. (Once again, another credible source suggests that close to 3 times the hydrogen would actually be required.)

And it's direct-to-diesel, instead of going through an intermediary, unless you count the processes related to additives. That means no losses for an extra step of conversion from an interim drop-in fuel to an actual fuel. And it's diesel, which is a bit more energy dense than gasoline, so that bodes well too. However, there's less hydrogen so more of the energy is coming from burning the carbon, so the ratio of CO_2 should be interesting to assess.

To be even more fair, we need to compare this to freight vehicles that use diesel for this point, rather than to passenger cars.

Tesla and other electric trucks are promising to reduce fuel expenses to about 6%, while Carbon Engineering's solution would increase them to at least 34%.

Greyrock makes no economic claims in its patent except to say that this is an appropriate technology for on-site, relatively small-scale generation of diesel where shipping costs are prohibitive, and that it could scale. That's not promising. Let's make an assumption that their one-step process to diesel costs the same as the one-step process to methanol in the absence of other information.

How much diesel would be created by this process? Once again, that's easy. The 272 kg of carbon will combine with roughly 46 kg of hydrogen to create 318 kg of diesel. Hmmm, that's a lot less than the 730 kg of methanol that would be created.

PROCESS	TONS	MWh-e FOR PROCESS	CO_2 DEBT (TONS)	AVERAGE COST
CO_2	1.00	1.54	0.35	$112
HYDROGEN	0.05	2.40	0.04	$238
CE E-DIESEL	0.32	1.07	0.02	$143
TOTAL		**5.01**	**0.41**	**$493**

Interesting so far. You get half as much fuel for half the cost with almost the came CO_2 debt, but the energy intensity is higher. How does that compare to an electric vehicle instead of a diesel vehicle? Well, let's look at the Tesla Semi, as a large portion of diesel is used by freight trucks and similar vehicles.

318 kg of diesel is about 96.9 gallons. Freight trucks in the USA were averaging 6.4 miles per gallon in 2010 (down from 9 miles per gallon in 1949, oddly). That means a freight truck could travel about 620 miles on the e-diesel created by this process.

How would the Tesla Semi do on the 5 MWh equivalent of energy? Well, they assert less than 2 kWh per mile, which we'll round up to 2 kWh per mile. Once again, being generous to the air-to-fuel and not-so-generous to the electric vehicle, the Tesla Semi would travel 4 times as far on the same energy. And once again, it would travel further on just the electricity inputs to the process excluding the natural gas inputs than the e-diesel solution would drive a truck.

trucks consumption progress

– 9 –

miles per gallon in 1949

– 6.4 –

miles per gallon in 2010

FUEL	MILES DRIVEN FOR FUEL	TONS CO_2	FUEL COST (NOT PRICE)	TONS CO_2 PER 10,000 MILES	FUEL COST PER 1,000 MILES
STANDARD DIESEL FREIGHT TRUCK	620	0.99	$307	15.89	$495
CE E-DIESEL FREIGHT TRUCK	620	0.40	$493	6.49	$794
BC ELECTRICITY IN TESLA SEMI	2,505	0.08	$225	0.30	$90

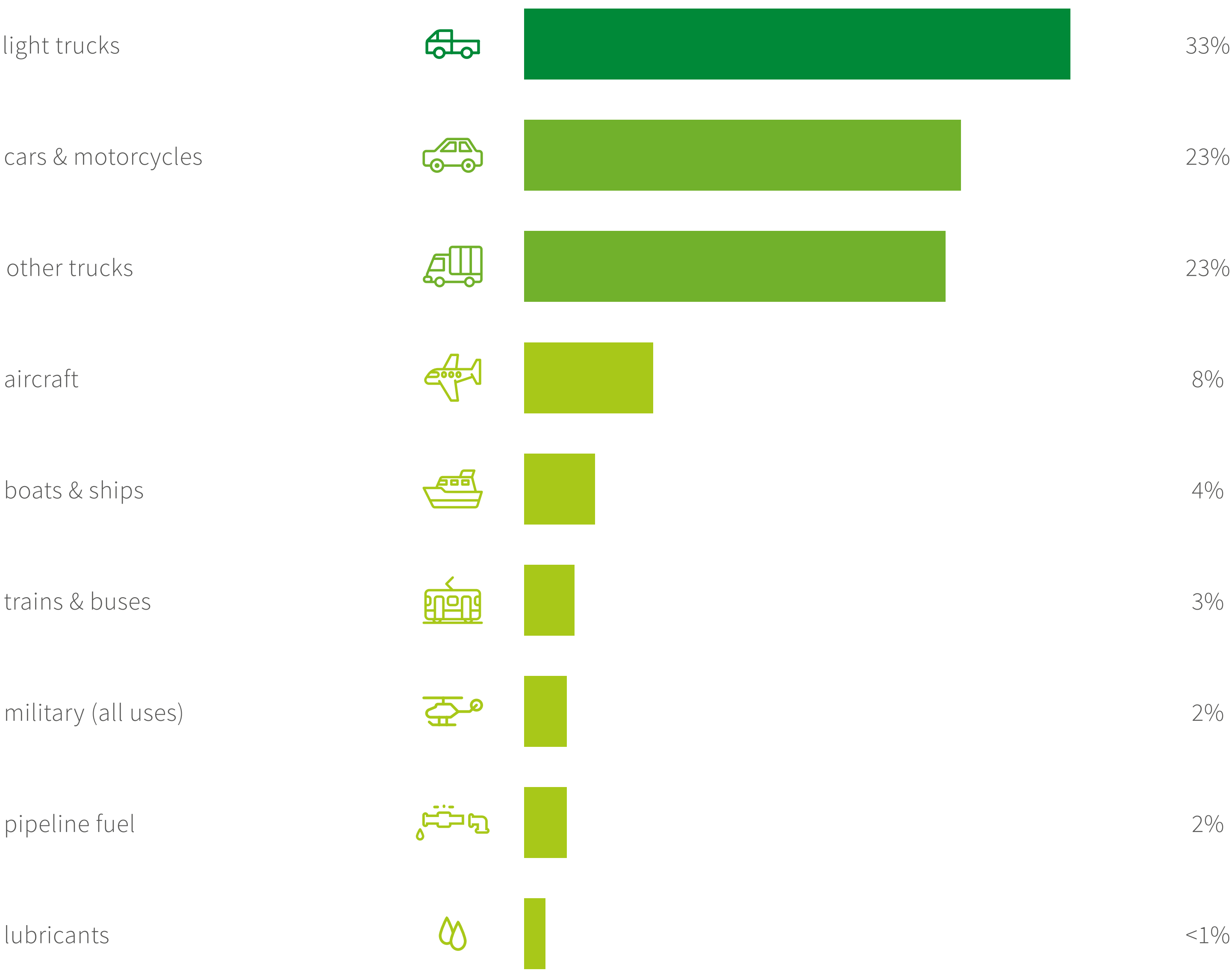
So, for the same energy inputs you could travel 4 times as far for a 5th the CO_2 emissions and well under half the cost in an electric truck. If you wanted to drive the same distance, it would cost you 6.5 times as much before distribution, storage and markup of the e-diesel and have 16 times the CO_2 emissions. The CO_2 emissions are better than standard diesel but 50% of bad is still bad, and it costs at least twice as much for e-diesel from Carbon Engineering when the alternative electric Semi is a quarter the cost per mile and has a fraction of the CO_2 emissions as well.

Per the American Transportation Research Institute, fuel represents about 21% of the costs of freight trucking. Tesla and other electric trucks are promising to reduce fuel expenses to about 6%, while Carbon Engineering's solution would increase them to at least 34%. Which is the freight industry going to be interested in?

Obviously, that's not a viable market unless your strategy is continuation of the internal combustion engine. I wonder who benefits from that? Certainly not the trucking industry which has to pay for the fuel, the consumers who have to pay for more expensive shipping or the world which has to pay for the higher than required CO_2 emissions. That's a very expensive 50% CO_2 emissions reduction when a very cheap 90% reduction is available

7.2. What about jet fuel for air travel?

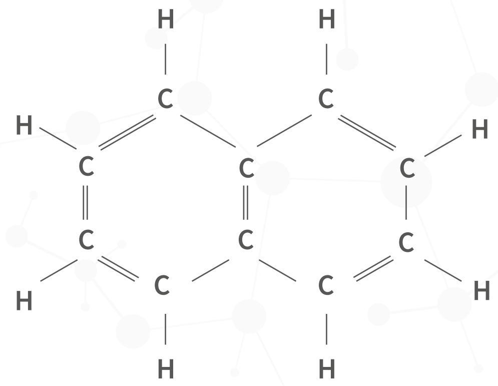
Transportation energy use by type



Source: U.S Energy Information Administration, Annual Energy Outlook 2017, Reference case, Table 36, estimates for 2016

So far, we've eliminated light trucks, cars and motorcycles, other trucks and (urban) trains and buses from the mix. Obviously pipeline fuel and lubricants aren't great choices for this either. That's eliminated about 84% of the US market for Carbon Engineering's air-to-fuel approach. But that still leaves 16%, right? Maybe there's some gold there?

Let's look at other use cases for petroleum transportation. Aircraft consume roughly 8% of petroleum per the US EIA, half of the remaining market. The Carbon Engineering process could be used to make an alternative aviation fuel. What do the large majority of jet and propellor planes use? Blends of kerosene which come in various flavours with carbon atoms in the 10-16 per molecule and a wide variance of hydrogen. The simplest is $C_{10}H_8$, but this is just the start.



Aviation fuels aren't defined by specific chemical compounds, but by characteristics of performance. As a result, anything Carbon Engineering could create would be feedstock for aviation fuel, not an aviation fuel in and of itself. That said, let's work out the same comparison.

Two fewer hydrogen in the ratio means less electricity to produce the hydrogen. Let's assume yet again that generously a variant of the Greyrock process uses the same energy to make kerosene.

PROCESS	TONS	MWh-e FOR PROCESS	CO_2 DEBT (TONS)	AVERAGE COST
CO_2	1.00	1.54	0.35	$112
HYDROGEN	0.04	1.92	0.03	$238
CE E-KEROSENE	0.31	1.07	0.02	$138
TOTAL		**4.53**	**0.40**	**$488**

Perhaps thankfully for Carbon Engineering, this isn't a place where electrification is expected to dominate and some form of synthetic or biofuels will be required for the coming decades. There are certainly small electric planes commercially available today and most of the majors are working on hybrid electric planes for intercity routes, but significant distances are still going to require burning fuel for quite a while. That said, they are competing with low-carbon fuels that have been around for a decade.

This table is a portion of the concluding costs table from a 2016 NREL report on alternative jet fuels. These pathways have been being explored fully by many organizations for 20 years. If Carbon Engineering wants to compete, these are its competitors in this space and their likely economics. The comparable pathway to the one Carbon Engineering is on is highlighted.

CATEGORY	PATHWAYS	INTERMEDIATE	INTERMEDIATE COST[A] ($/GAL)[($/GGE)]	FINAL JET FUEL COST ($/GAL)[($/GGE)]
ATJ	ETHANOL TO JET	ETHANOL	$1.4-$4.2($2.1-$6.4)	$4.1-$14.4($3.8-$13.4)
	N-BUTANOL TO JET	N-BUTANOL	$2.9-$4.1($3.5-$5.0)	$4.1-$7.5($3.8-$7.0)
	ISO-BUTANOL TO JET	ISOBUTANOL	$3.7($4.5)	$5.1-$6.4($4.8-$6.0)
OTJ	METHANOL TO JET	METHANOL	$1.5($3.0)	NOT AVAILABLE
	HRJ	BIO-OIL	$0.9-$22.4	$2.6-$34.7($2.4-$32.0)
	CH	BIO-OIL	$4.8-$7.7	$4.8($3.3-$4.5)
	PYROLYSIS	PYROLYSIS OIL	$1.1-$3.4($0.8-$3.7)	$3.9
GTJ	FT TO JET (BTL)	SYNGAS TO HYDROCARBONS	$1.9-$2.5($3.1-$6.2)	$6.2($5.8)
	CTL	SYNGAS TO HYDROCARBONS	$2.2-$2.4($1.9-$2.0)	$2.2-$2.6
	CBTL	SYNGAS TO HYDROCARBONS	($2.9-$3.1)	($2.7-$3.1)
	GAS FERMENTATION	SYNGAS TO ETHANOL	$1.5	NOT AVAILABLE
STJ	CATALYTIC CONVERSION OF SUGARS APR PATHWAY	HYDRO-CARBONS	($4.1-$9.7)	NOT AVAILABLE
	CATALYTIC CONVERSION OF SUGARS APR PATHWAY	DMF AND HMF	$6.2-$9.5($7.1-$11.8)	NOT AVAILABLE
	BIOLOGICAL CONVERSION	FATTY ACIDS AND FARMESENE	$6.8	$4.3-$17.3($4.0-$23.3)

note: [A] the cost numbers were inflated to 2011 U.S dollars

That 307 kg of intermediate-stage kerosene that Carbon Engineering is creating represents about 84.4 gallons at a cost of about $6 USD per gallon. In 2016, equivalent processes based on biomass were running in the $1.9 to $2.5 USD per gallon range, well under 50% of the cost that this work is suggesting for Carbon Engineering's approach. Jet fuel is running about $1.91 per gallon right now, so Carbon Engineering is doubly out of the market. It's more expensive than existing alternatives that are already in play and at least 3 times more expensive than existing jet fuel. For our comparison, we'll use the intermediate high-end of the range $2.5, knowing that it's incomplete, but will at least give a sense of what's going on.

But what about CO_2? After all, this is supposed to be carbon emissions reduction technology. So far, it's not working, but maybe in alternative jet fuels it actually has a value proposition?

FUEL	MILES FLOWN FOR FUEL	TONS CO_2	FUEL COST (NOT PRICE)	TONS CO_2 PER 10,000 MILES	FUEL COST PER 1,000 MILES
JET FUEL (KEROSENE)	17	0.81	$161	481.8	$9,550
CE E-KEROSENE	17	0.40	$487	234.1	$28,873
NREL COMPARATIVE E-KEROSENE	17	0.04	$211	23.9	$12,413

Well, not really. The NREL study also does full workups on CO_2 intensity of the different pathways. In exactly the same space as Carbon Engineering of creating liquid hydrocarbon fuels, but using biomass instead of capturing all the CO_2 from the air with giant fans, CO_2e emissions are 5% of jet fuel already, and at a price point well under 50% of Carbon Engineering's per this workup.

For aircraft, Carbon Engineering's solution is 3 times as expensive (at minimum) and only eliminates 50% of the emissions of petroleum-derived jet fuel. It's 2.3 times as expensive as existing alternatives and has 10 times the CO_2 emissions. And that's without factoring in the likely much higher hydrogen requirements.

8.

Where could carbon direct air capture make sense?

Air carbon capture which is actually a climate solution makes sense under the following conditions:

1. It's **co-located with an industrial site** which requires CO_2.
2. The site **needs tons of CO_2** as feedstock per day, perhaps for concrete.
3. The site **doesn't have access to a lot of biomass** because it's already a concentrated source of carbon which you can bind with oxygen cheaply and easily. Greenhouses probably don't need it.
4. The site **generates a lot of waste industrial heat** or biomass to tap for energy so that you don't have to burn a lot of fossil fuels for processing.
5. The site has access to **a lot of very cheap electricity** that's also carbon neutral to power fans.
6. **A pipeline for CO_2 to the site isn't viable.** CO_2 is a purchasable commodity. Per one source it costs about $40 per ton to get it trucked in. If you have a pipeline, then it works out to $0.77 per ton per mile and $1.50 per ton, but with another big capital cost. That's on top of the commodity price for industrial CO_2 of $30 to $50 per ton, if memory serves. Smaller volumes are much more expensive. When you start seeing $90 per ton delivered, you can see that there might be some circumstances in which $100 per ton might be worth doing, and that if you can eliminate energy costs it becomes reasonable. That's if the capital cost wasn't going to be absurd; you need an awful lot of CO_2 in order to justify millions in capital costs.

But even then, let's look at that greenhouse example. For greenhouses, you only need concentrations at 3–4 times atmospheric levels. That's pretty easy to manage with a simpler tech than the Carbon Engineering 'magic bullet'. Just burn some biomass, probably dried waste stems, and capture the CO_2 from the biomass smoke which has much more density, once again. Only one of the three CO_2 capture mechanisms Carbon Engineering uses would be required. Oh, and get some waste heat for warming the place as necessary.

So what sites might actually be useful for Carbon Engineering's solution as it's designed? Let's return to the 2012 paper the principals published in the Royal Society journal:

An AC facility operating on low-cost 'stranded' natural gas that is able to provide CO_2 for enhanced oil recovery at a location without other CO_2 sources might be competitive with post-combustion capture in high-cost locations such as Canadian oil sands operations.

Years ago, the principals in Carbon Engineering realized that their market was likely the fossil fuel industry. From their new investors' perspective, this is a great technology. It uses a lot of one of their products, possibly even a reserve that they have no economic use for today. It allows them to get more of another of their products, oil, out of tapped-out wells. And it gives them a nice big marketing win in headlines that they are saving the planet from global warming.

That's a trifecta of goodness for the fossil fuel companies. Not so much for the rest of the world. That 10% tax of emissions on the natural gas isn't looking so good now.

What would net emissions for using CO_2 for enhanced oil recovery look like? Per a high-citation 1993 study on the subject:

For every kilogramme of CO_2 injected, approximately one to one quarter of a kilogramme of extra oil will be recovered.

That's interesting. How much CO_2 is created from a 0.25 kg of oil, well to wheels? Well, just burning oil produces about 3.2 times the CO_2 by weight excluding processing. Processing is a 10% to 20% hit depending on the quality of the crude. So that 0.25 kg of CO_2 turns into about 0.8 kg of CO_2 and processing adds another chunk, bringing it perhaps to 90%. With the 10% emissions tax on the natural gas, that means that **there is zero net removal of CO_2 from the atmosphere if air carbon capture CO_2 is used for enhanced oil recovery.** And that's at a cost of $94 to $232 for the air carbon capture portion alone. That's at the low end of the range for enhanced oil recovery, so it will be worse than that. All of the negative externalities of fossil fuels persist indefinitely.

9. What could this money and energy be used for instead?

All of this investment and energy consumption begs the question, “What if it were used for something more productive?

9.1. What if we just used the 7.4 MWh in an electric car?

Electric cars take about 15-30 kWh to travel 100 miles. With 7.4 MWh, that’s 25,000-50,000 miles. Let’s work with the best case for air-to-fuel and the worst case for electricity.

FUEL	MILES DRIVEN FOR FUEL	TONS CO_2	FUEL COST (NOT PRICE)	TONS CO_2 PER 10,000 MILES	FUEL COST PER 1,000 MILES
METHANOL ADDITIVE	3,700	0.42	$916	1.14	$248
METHANOL TO GASOLINE	3,400	0.60	$1,200	1.76	$353
BC ELECTRICITY IN EV	24,700	0.11	$333	0.05	$14

Those are some interesting apples-to-apples numbers. The methanol path costs 18 times more for a unit of distance traveled and has 23 times the CO_2 emissions for fuel as the same starting energy used directly in the worst-case EV. The methanol to gasoline path is worse at 25 times the cost and 35 times the emissions.

What if we just used the electricity that the process consumes, not the natural gas? That’s almost exactly 6 MWh and you could drive almost 20,000 miles on it without burning any natural gas at all.

9.2. What if we built a wind farm?

Carbon Engineering has so far accrued about $6 million USD from the Canadian government and $68 million from the oil and gas majors among others. The company spent a bunch of money already to get to that point, so let's assume that it is up at $80 million in funding to date, likely a conservative number. Crunchbase indicates over $82 million so far, so that's accurate.

What if that $80 million had been spent on a wind farm? The rule of thumb is $2 million per MW of capacity, so that's a 40 MW capacity wind farm. In a year, it could generate about 150 GWh of electricity and electric cars could drive about 470,000 miles on the electricity, about 130 times as far as cars could be driven on Carbon Engineering's air-to-fuel plan.

10.

Who benefits from this?

The BBC magic bullet article has a very telling point about Carbon Engineering:

*It has now been boosted by $68m in new investment from **Chevron, Occidental and coal giant BHP.***

What are those? Are they all fossil fuel companies? Yes, of course. What could they want with an investment in air carbon capture of one of their products' primary wastes, CO_2? One that uses massive amounts of one of their primary products? And makes them look good on casual inspection?

Chevron had a revenue of $159 billion in 2018. Occidental made $17.8 billion. BHP made $43.6 billion. So that's $220 billion combined annual revenue vs $68 million in 'investment'. That's about 0.03% of their annual revenue going to this initiative. And they didn't provide the entire $68 million, so it's less of their annual revenue.

Let's compare this to another recent Chevron-related headline: *Chevron to buy Anadarko in $33-billion bet on shale oil and LNG — the biggest energy deal in four years.* That's from Canada's National Post, but it's repeated in various forms in business outlets globally. How much bigger is $33 billion than $68 million? Almost 500 times bigger. That's 20% of Chevron's annual revenue. That's a real investment in real business for Chevron. The less than $68 million split between three companies is advertising dollars. It doesn't even rise to the level of a side bet. You can imagine it being handled by the executive in charge of marketing, or perhaps someone's executive assistant.

As with almost all carbon capture approaches, the only group which still thinks it has merit is the fossil fuel industry. They spend a tiny fraction of their money so that they can tout the wonders of their technology around the world while continuing to produce gigatons of CO_2e annually.

Chevron had a revenue of

$159

billion in 2018

In reality, this technology would use 70,000 households' worth of natural gas in order to capture a million tons of CO_2 a year. It's more a new market for natural gas than a solution for climate change.

11.

Who came up with this idea?

So we have a technology that burns so much natural gas that they produce and must capture 500 tons of CO_2 for every 1,000 they capture from the air. And its natural market is to increase oil extraction. And the alternative to do nothing is free and has lower net carbon emissions. Why would anyone think this is a good idea? It's a really smart bad solution, but deeply unwise if you actually care about global warming.

Enter Dr. David W.Keith, stage right. He's the primary engineer behind Carbon Engineering. His name is on the published papers. He's mentioned in all the articles. He's acting chief scientist and on the Board of Directors. He's a very bright, very credentialed, very connected guy. He took first in Canada's national physics competition, picked up an MIT prize for experimental physics, and Time Magazine picked him as one of its Heroes of the Environment.

Wait. What? The guy who just sold a net-loss air carbon capture technology using natural gas to people who will use it for enhanced oil recovery is a Hero of the Environment? Why does that sound so familiar? Perhaps it's because I've published a series of pieces recently on the ill-founded, cherry-picked, and biased views of another of Time Magazine's Heroes of the Environment, Michael Shellenberger, who also doesn't like renewable energy as a solution, preferring nuclear in its place. What is it with Time Magazine's HotEs that they get things wrong so badly?

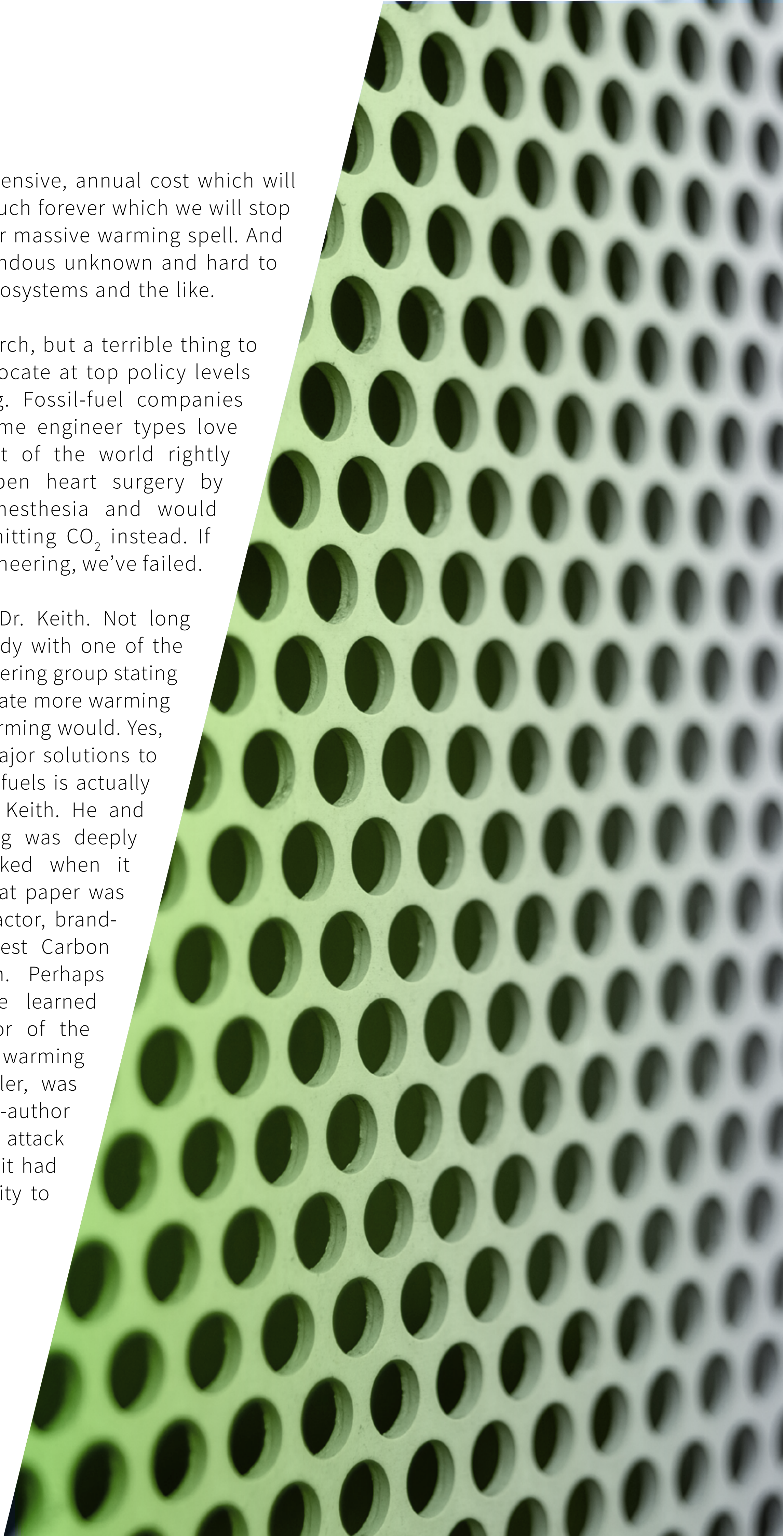
Dr. Keith has game in this regard. He runs The Keith Group, affiliated with Harvard and funded by a bunch of folks including the Gates Foundation (which really ought to look twice at giving money to it) and is devoted to a focus on the science and public policy of solar geoengineering.

What's solar geoengineering? That's putting lots of stuff in the atmosphere to avert warming by masking the effects of CO_2, which most ethicists and pragmatists agree will do three things. First, it will mean we keep burning fossil fuels and increasing the CO_2 concentration of the atmosphere further with all of the detriments to marine life and other things that comes with that.

Second, it will be an expensive, annual cost which will have to be done pretty much forever which we will stop doing and lead to another massive warming spell. And finally, it will have tremendous unknown and hard to predict impacts on our ecosystems and the like.

It's a great thing to research, but a terrible thing to do. Keith is a strong advocate at top policy levels for solar geoengineering. Fossil-fuel companies love geoengineering. Some engineer types love geoengineering. The rest of the world rightly considers it akin to open heart surgery by a 9-year-old without anesthesia and would prefer to simply stop emitting CO_2 instead. If we ever resort to geoengineering, we've failed.

But there's more about Dr. Keith. Not long ago he co-authored a study with one of the members of his geoengineering group stating that wind farms would create more warming in the USA than global warming would. Yes, that's right. One of the major solutions to CO_2 emissions from fossil fuels is actually a problem, according to Keith. He and his collaborator's thinking was deeply shoddy and much mocked when it came out. Once again, that paper was in Joule, the no-impact-factor, brand-new journal that his latest Carbon Engineering paper is in. Perhaps there's something to be learned from that? The co-author of the wind-farms cause global warming nonsense paper, Lee Miller, was lead author with Keith as co-author in another much-derided attack on wind energy, claiming it had massive limits to the ability to provide power.



12.

What do the experts say?

Returning to Dr. Mark Z. Jacobson, who was quoted earlier in the case study, he doesn't include air carbon capture in his models for a 100% renewable future. He's globally acknowledged for his team's modeling of 100% renewables by 2050 for all US states and the majority of countries globally, providing a clear and sensible policy path. Why doesn't Jacobson include air carbon capture? He explains it in *Why Not Synthetic Direct Air Carbon Capture and Storage (SDACCS) as Part of a 100% Wind-Water-Solar (WWS) and Storage Solution to Global Warming, Air Pollution, and Energy Security.*

By removing CO_2 from the air, SDACCS does exactly what WWS generators, such as wind turbines and solar panels, do. This is because WWS generators replace fossil generators, preventing CO_2 from getting into the air in the first place. The impact on climate of removing one molecule of CO_2 from the air is the same as the impact of preventing one molecule from getting into the air in the first place.

The differences between WWS generators and SDACCS equipment, though, are that the WWS generators also (a) eliminate non-CO_2 air pollutants from fossil fuel combustion; (b) eliminate the upstream mining, transport, and refining of fossil fuels and the corresponding emissions; (c) largely reduce the pipeline, refinery, gas station, tanker truck, oil tanker, and coal train infrastructure of fossil fuels; (d) largely eliminate oil spills, oil fires, gas leaks, and gas explosions; (e) substantially reduce international conflicts over energy; (f) reduce the large-scale blackout risk due to the distributed nature of many WWS technologies; and so-on.

SDACCS does none of that. Its sole benefit is to remove CO_2 from the air. To do that, it costs more than renewable energy.

Triggered in minor part by the series of articles this report is based on, Dr. Jacobson updated his calculations based on the use of gas generation by Carbon Engineering, and provided an updated perspective.

In the case where the CO_2 is captured from the gas plant, 36% of all CO_2 captured is effectively re-emitted to the air. The direct cost of CO_2 captured from the ambient air per unit grid energy used to produce the CO_2 is still 2.2 to 10 times the cost of preventing the emissions in the first place with a wind turbine. The air pollution plus *energy social cost of this SCACCS system is $192 to $398/MWh higher than that of wind.*

In sum, so long as grid emissions occur, SDACCS will always increase air pollution no matter how low its cost, and SDACCS will always increase CO_2e emissions until its direct cost is much lower than that of WWS technologies. Further, it always increases the mining, transport, and processing of fossil fuels compared with using WWS instead.

All of that electricity that's used to move all that air to find the 411 parts per million could be used for productive purposes and be much more efficient at removing CO_2 from the air along with a bunch of other benefits. Seems obvious. Not to David Keith or his fossil fuel sponsors though.

What about carbon capture at fossil fuel source of generation of electricity instead? You know, where all that CO_2 is concentrated in the first place? Well, a recent study led by Sgouris Sgouridis at Khalifa University in Abu Dhabi found it wasn't worthwhile either.

"We show that constructing CCS power plants for electricity generation is generally worse than building renewable energy plants, even when we include the effects of storage systems like batteries and hydrogen," says Sgouridis. The researchers also discuss significant challenges that CCS promoters would need to address to upscale the technology sufficiently for it to become useful. "These challenges should make the energy policy community very apprehensive about relying on such a solution rather than considering it as a last resort," Sgouridis says.

That 50% of natural gas CO_2 emissions required to fuel the Carbon Engineering air carbon capture? That's what the Sgouridis paper is talking about; it's the same thing. Modeling and peer-reviewed research is showing that even the 97.5% CO_2 capture from the natural gas combined heat and power solution isn't worth it.

The first rule of being deep in a hole is to stop digging. Wind and solar electricity being used for productive purposes is much better than using it for air carbon capture. It's not like the jury is out on this, except for people like David Keith and Chevron.

13.

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Michael Barnard is Chief Strategist with TFIE Strategy Inc. He works with startups, existing businesses and investors to identify opportunities for significant growth and cost takeout in our rapidly transforming world. He has been a global business strategist, systems engineer, business architect and solutions architect with a global, Fortune 500 technology consultancy, holding leadership positions in North American, South America and Asia. He was Senior Fellow - Wind (Distance) with the Washington-based Energy and Policy Institute. He is editor of The Future is Electric, a Medium publication. He regularly publishes analyses of low-carbon technology and policy in sites including Newsweek, Slate, Forbes, Huffington Post, Quartz, CleanTechnica and RenewEconomy, and his work is regularly included in textbooks. Third-party articles on his analyses and interviews have been published in dozens of news sites globally and have reached #1 on Reddit Science. Much of his work originates on Quora.com, where Mike has been a Top Writer annually since 2012. He's available for consulting engagements, speaking engagements and Board positions.

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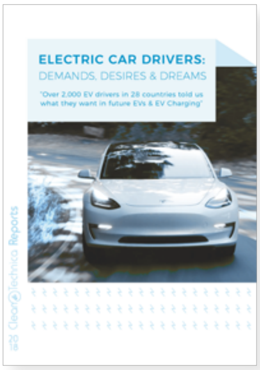

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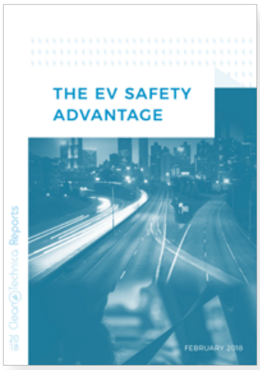

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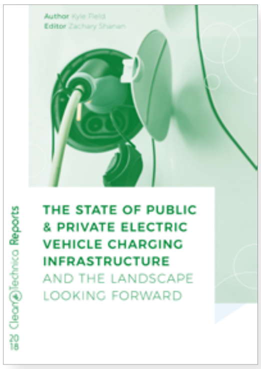

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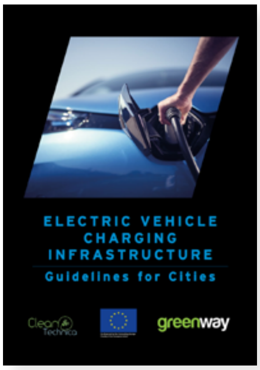

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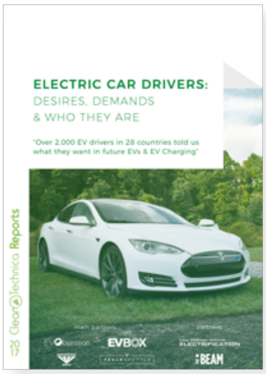

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