Cities, future fossil fuel use, CCUS, & nuclear energy
MIT 11.165/477, 11.286J

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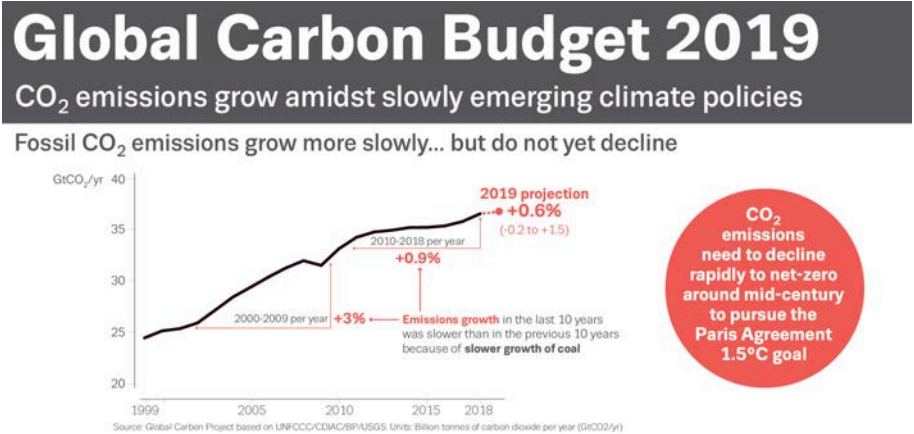
Materials for today

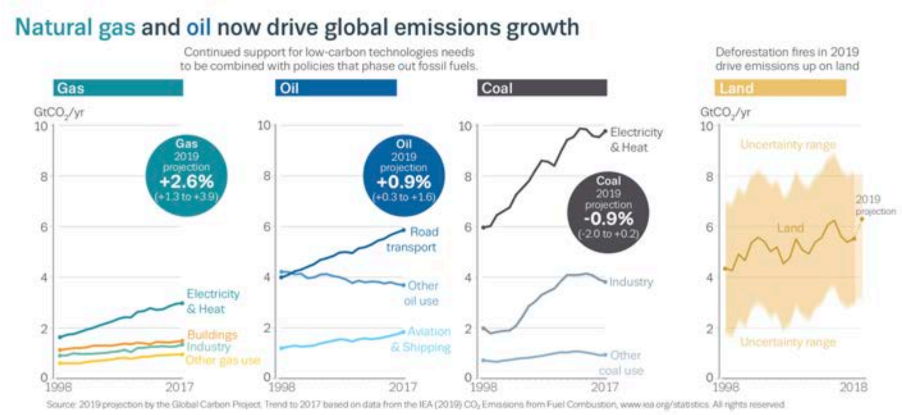
- David Roberts. Sucking carbon out of the air won't solve climate change, June 2018. URL.
- David W. Keith, Geoffrey Holmes, David St Angelo, and Kenton Heidel. A Process for Capturing CO2 from the Atmosphere. Joule, 2(8):15731594, August 2018. ISSN 2542-4785, 2542-4351. URL.
- Ryan Orbuch. Stripes first negative emissions purchases, May 2020. URL.
- Nestor A. Sepulveda, Jesse D. Jenkins, Fernando J. de Sisternes, and Richard K. Lester. The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. Joule, 2(11):24032420, November 2018. URL.
- John Mecklin. The Diablo Canyon nuclear plant: assessing the seismic risks of extended operation, August 2022. URL.

Cities exist within a much larger energy system;
Context decides what we try to pursue in cities.

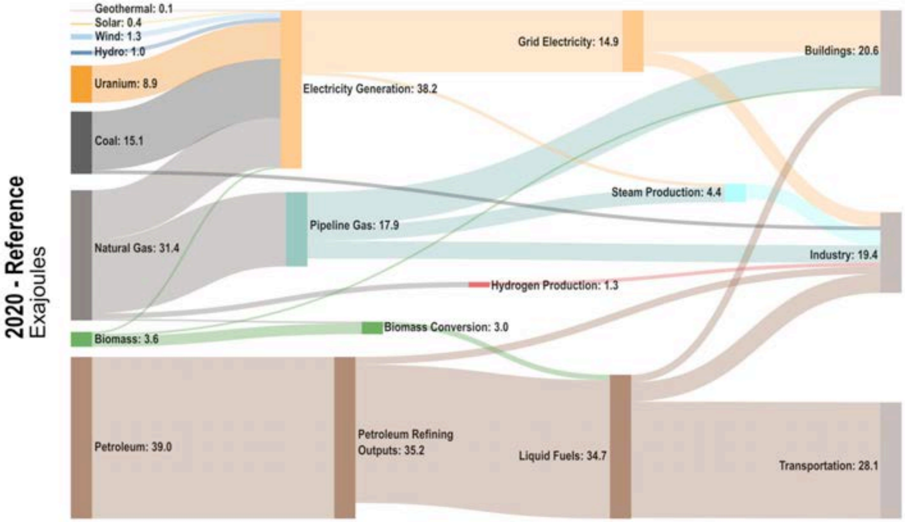
Global Carbon Project



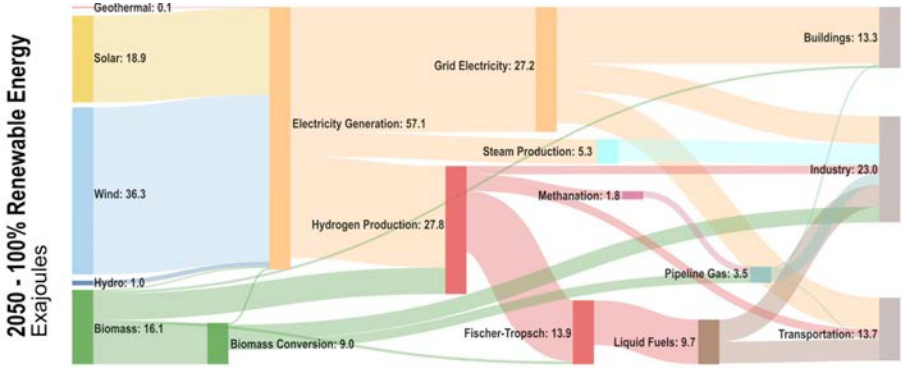
Global Carbon Project



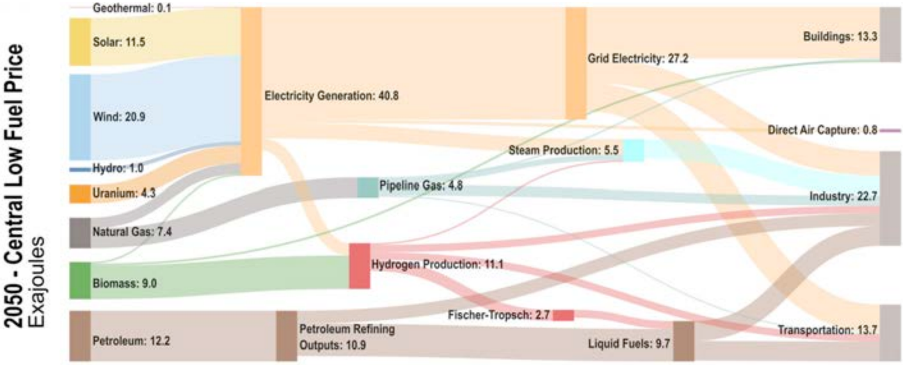
Williams et al 2021 decarbonization pathways



Williams et al 2021 decarbonization pathways



Williams et al 2021 decarbonization pathways



Note: in this paper, the central (least-cost) and low fuel price scenario means that this is the maximum amount of fossil fuels that could be used. Remaining use of petroleum and natural gas (both -75%).

Williams et al 2021 decarbonization pathways

How do we go from a reference case to a carbon-neutral pathway that still has fossil fuels?

1. lowering final energy use
2. decarbonizing electricity
3. switching from FF to electricity
4. carbon capture, util. & storage

Carbon capture, utilization & storage

Cons:

- pushed by fossil fuel interests as a way to continue emissions
- not competitive, i.e., higher cost than existing renewable alternatives
- no fundamental economic value to storing carbon
- carbon taxes and prices have not proven to be politically viable

Pros:

- short term: high fossil fuel prices
- long-term: need to reduce carbon concentrations in the atmosphere (current levels 415 ppm)

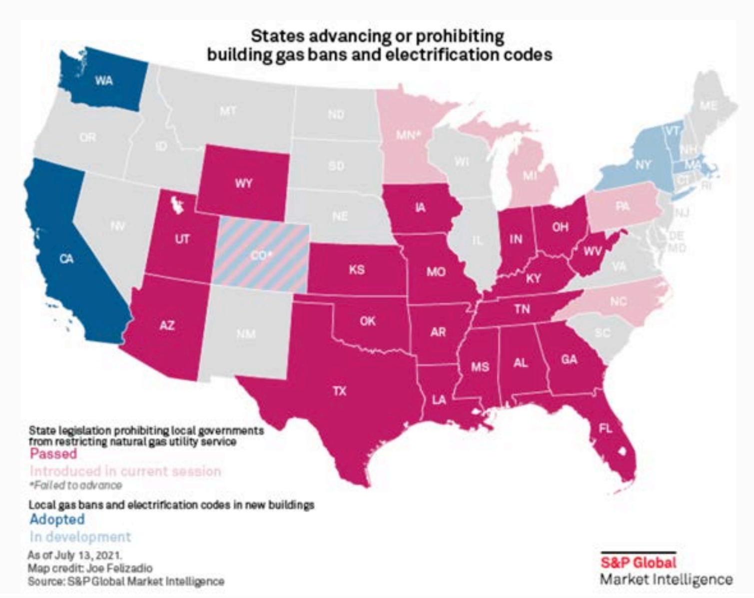


Figure: S&P Market Intelligence, 2021

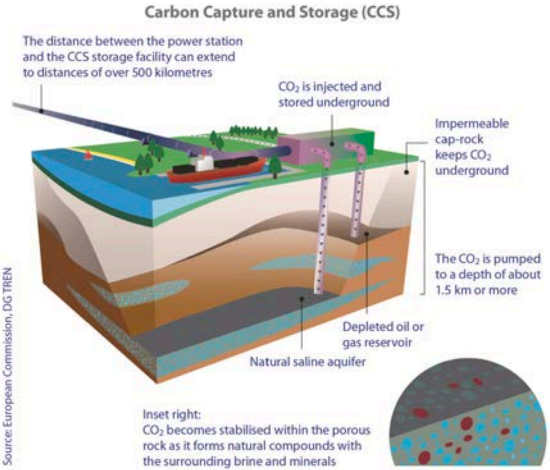


Fig. 11. An overview of underground carbon storage. Though this diagram indicates compressed CO_2 comes from a "power station," it may also be produced by an industrial facility or a cluster of facilities. Image CC BY 4.0 European Commission (permission).

CCUS in the lithosphere, geosphere diagram (Rissman et al)

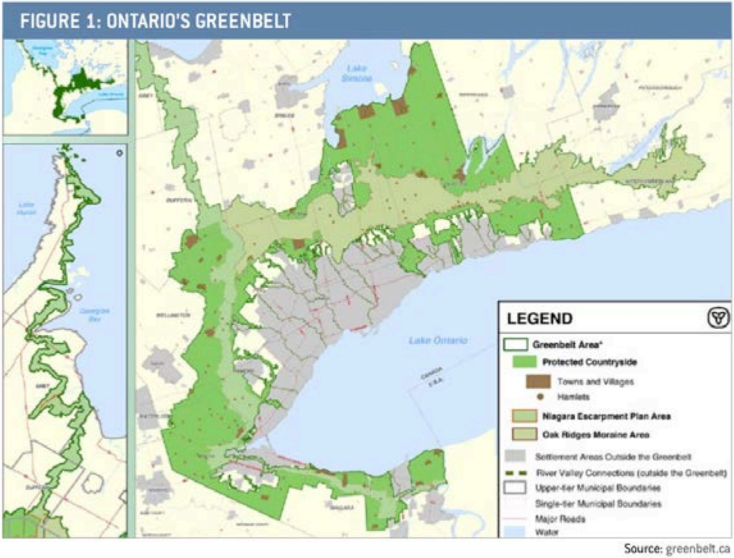


Figure 1 from Tomalty report

Agricultural soils (MIT CGC terrestrial carbon)

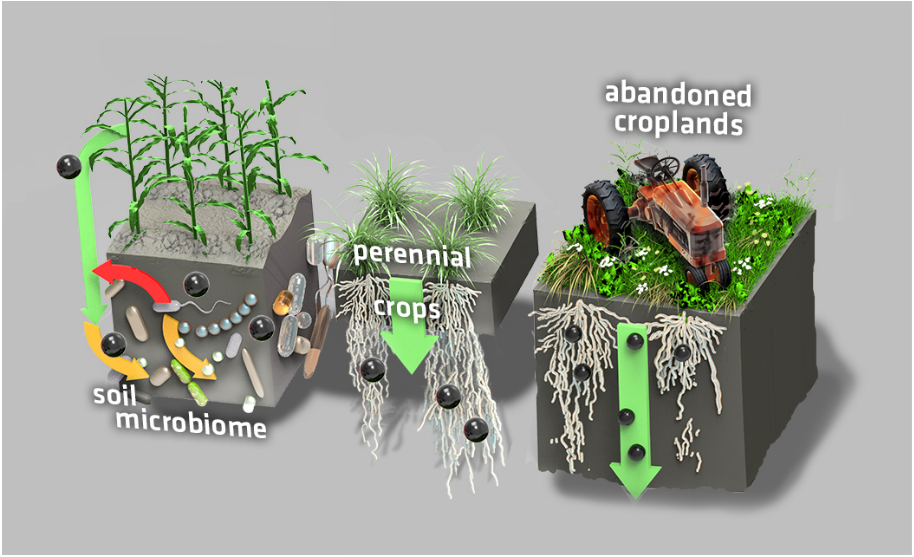


Diagram courtesy of MIT Climate Grand Challenges.

Forest sequestration (MIT CGC terrestrial carbon)

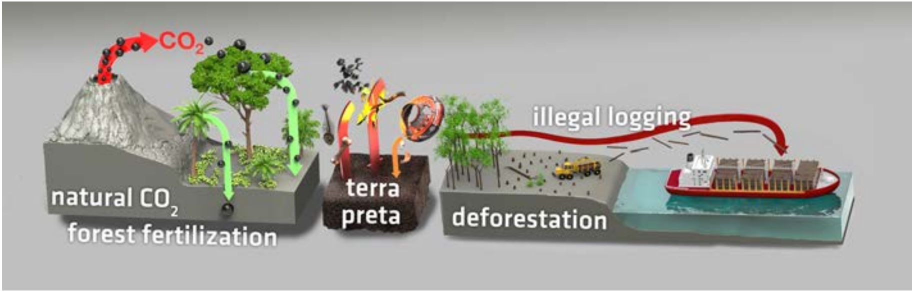


Diagram courtesy of MIT Climate Grand Challenges.

Hydrosphere (MIT CGC terrestrial carbon)

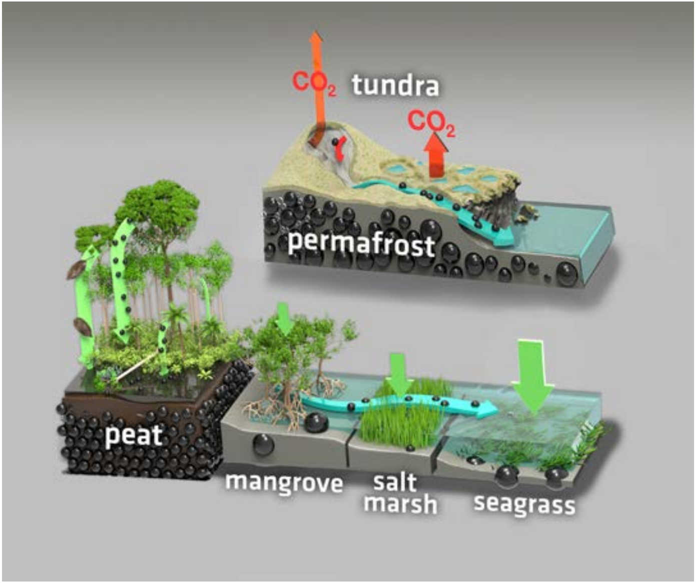
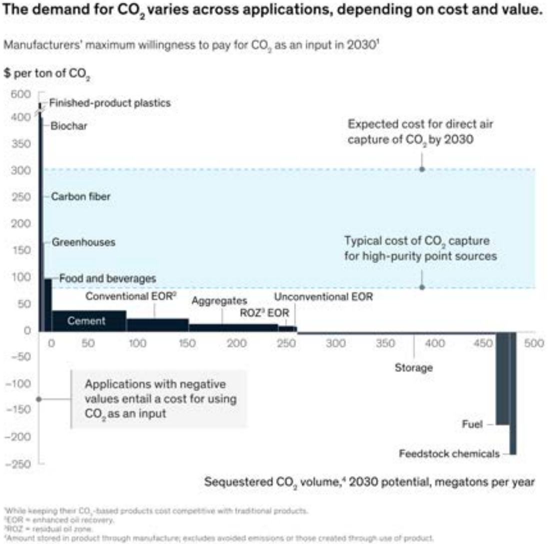


Diagram courtesy of MIT Climate Grand Challenges.

McKinsey 2020 report on CCUS

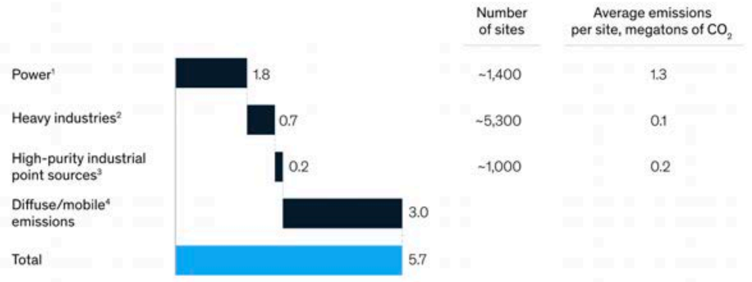


McKinsey 2020 report on CCUS

Exhibit 3

In the United States alone, potential industrial sources for carbon capture, use, and storage are plentiful, though they vary in terms of CO_2 concentration.

Total CO_2 emissions in United States, 2018, metric gigatons of CO_2



[1]Includes gas and coal.
[2]Includes oil and gas production, storage and distribution, refining, cement, iron/steel, and chemical production (except as noted in high-purity sources).
[3]Includes natural-gas processing, ethanol, ammonia, hydrogen, and pulp and paper production.
[4]Diffuse/mobile sites number in the millions, with average emissions per site of ~0.001 megatons of CO_2; includes transportation (eg, cars, trucks, aircraft, ships), residential/commercial use, and agriculture.
Source: "Greenhouse Gas Reporting Program (GHGRP)," US Environmental Protection Agency, epa.gov

Carbon Engineering (David Keith and others)

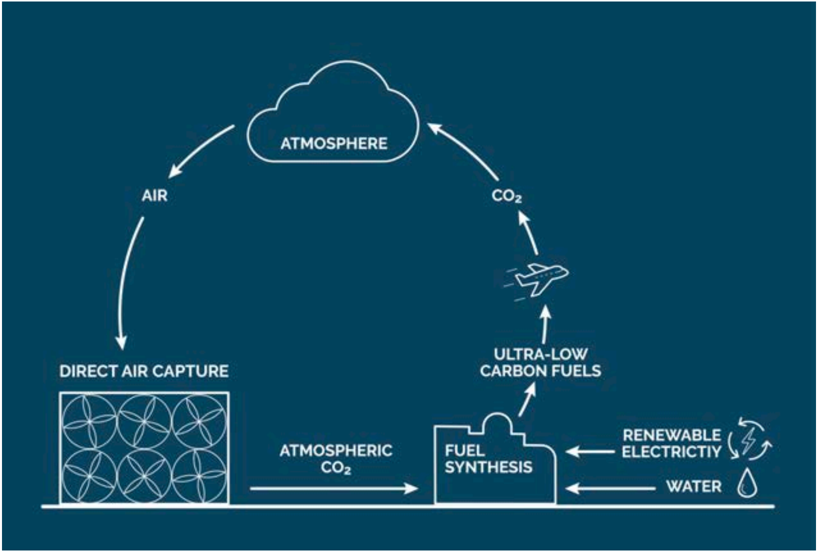
ABOUT AIR TO FUELS™

CE's process delivers synthetic, ultra low carbon fuels – such as gasoline, diesel, and jet-A – out of air, water and renewable electricity.

Using an approach called the AIR TO FUELS™ solution, CE can produce renewable fuels that are drop-in compatible with today's infrastructure and engines and are almost completely carbon neutral. The process integrates four growing fields – renewable electricity generation, Direct Air Capture, green hydrogen production, and sustainable fuel synthesis – to deliver a highly scalable, clean fuel solution. It delivers drop-in ready fuels that have an ultra-low lifecycle carbon intensity and are cost-competitive with biofuels.

As a leader in large-scale Direct Air Capture technology, with an AIR TO FUELS™ pilot plant that has been producing clean fuel since 2017, CE is uniquely positioned to deliver this solution. We are open to best-in-class suppliers and partners in renewable electricity generation, green hydrogen, fuel synthesis, and plant development to partner with us on commercial projects.

Carbon Engineering (David Keith and others)



Carbon Engineering (David Keith and others)

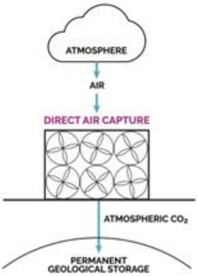
01 STANDALONE GEOLOGICAL STORAGE

CO_2 removed with DAC can be securely stored in saline formations or depleted oil and gas wells to deliver permanent carbon removal.

Saline Formations are large layers of rocks with porous spaces that are isolated deep underground and contain salt water. The practice of storing CO_2 in saline formations has been examined extensively by industry, academics, and government agencies and has been found to present a long-term solution for CO_2 storage with immense capacity.

Depleted oil and gas fields that are no longer productive also make ideal geological storage sites due to their established trapping and storage characteristics and the availability of extensive geologic data from when they were operational wells.

Permanently storing atmospheric CO_2 in saline formations and depleted oil and gas wells allows us to achieve what is known as carbon dioxide removal, or negative emissions. A Direct Air Capture facility built this way has the sole purpose of removing CO_2 from the atmosphere. Near-term, this will allow us to reduce the net amount of CO_2 that is being released into the atmosphere and help us get to net zero much faster. In the future, once CO_2 emissions have been reduced dramatically, these facilities could be used to reduce the overall level of CO_2 in the air back to safe levels.



Carbon Engineering (David Keith and others)

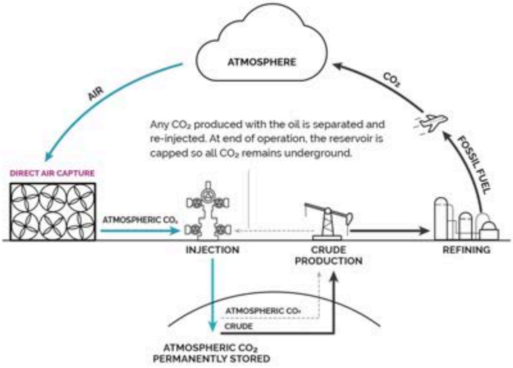
02 ENHANCED OIL RECOVERY

Atmospheric CO_2 captured from Direct Air Capture plants can be permanently stored in oil reservoirs during oil production.

Injecting CO_2 into oil reservoirs is a common practice, known as enhanced oil recovery, that has been performed by the oil and gas industry since the 1970's. While historically enhanced oil recovery was not performed to achieve environmental benefits, when the CO_2 used has been removed from the atmosphere using Direct Air Capture technology, it can dramatically reduce the overall carbon footprint of the oil produced.

Additionally, new laws and regulations – such as California's Low Carbon Fuel Standard – are now giving guidance and incentive to experienced operators to ensure the CO_2 is stored permanently during the process. When performed this way, the permanent injection of atmospheric CO_2 into the reservoir can partially or completely counteract the emissions from the oil produced. Or, if the quantity of atmospheric CO_2 permanently stored is greater than what is produced through refining and use of the oil, this activity can produce fuels for transportation while also generating net negative emissions. For readers familiar with life-cycle analysis, this means that, depending on factors such as the pattern of the well and the operation of the oil reservoir, DAC with enhanced oil recovery can produce fuels with low, zero, or even negative life-cycle "carbon intensity".

Carbon Engineering (David Keith and others)



If the amount of CO_2 injected and stored is equal to the amount produced when the oil is refined and used, the full process is carbon neutral. If more CO_2 is injected than what is produced, the process results in a net reduction of CO_2 in the atmosphere.

Stripe's negative emissions commitment

Stripe's first carbon removal purchases

May 18, 2020

Ryan Orbuch
Climate

Spring 2021 Update: Request for Projects

We're searching for new carbon removal projects that meet our target criteria to apply for our next round of purchases.

Request Application ›

To mitigate the threat of climate change, the majority of climate models agree that the world will need to remove carbon dioxide from the atmosphere on the scale of approximately 6 gigatons of CO2 per year by 2050. That's roughly the equivalent of the United States' annual emissions.

Last year, Stripe announced our Negative Emissions Commitment, pledging at least $1M per year to pay, at any price, for the direct removal of carbon dioxide from the atmosphere and its sequestration in secure long-term storage. We've since built a small team within Stripe to focus on creating a market for carbon removal by being an early customer for promising carbon removal technologies.

Stripe's negative emissions commitment

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Stripe's negative emissions commitment

Stripe carbon removal target criteria

Criteria	Today	Target by 2040
Sequestration beyond the biosphere Takes advantage of carbon sinks less constrained by arable land, e.g. carbon mineralization	Yes	Yes
Volume Has a path to being a meaningful part of the carbon removal solution portfolio	–	> 0.5 gigatons per year
Cost Has a path to being affordable at scale	–	< $100 per ton
Permanence Stores carbon permanently	> 1,000 years	> 1,000 years

Stripe's negative emissions commitment

Verifiability Uses scientifically rigorous and transparent methods for verification	Modeled or measured directly	Modeled and measured directly
Quality and safety Is globally responsible, considering possible risks and negative externalities	Path to high	High
Net-negative lifecycle Reduces net atmospheric CO_2 expressed as a ratio subject to appropriate boundary conditions: [Emissions produced] : [CO_2 removed from the atmosphere]	Negativity ratio ≤ 1	Negativity ratio < 1

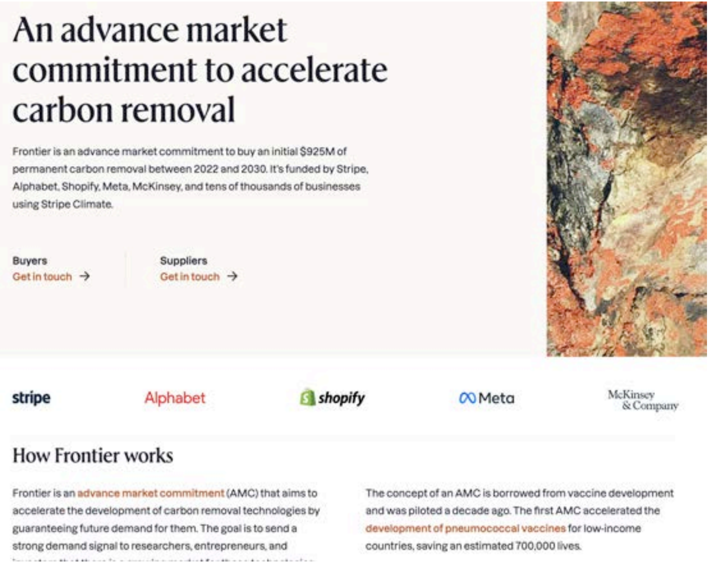
> We are very open to supporting projects that focus on either capture or storage, so long as they have a path to a holistic carbon removal solution that meets the above criteria.

Stripe's negative emissions commitment

Call to action

Our goal is not only to remove carbon from the atmosphere, but to become an early member of an ecosystem of funders and founders who will invent ways to solve the world's largest collective problem. We continue to search for great projects, purchasers, and experts. Please reach out to us to work together on this effort or to give us any feedback. We can be reached at climate@stripe.com. (And if you're an engineer or designer who cares about climate impact, consider joining our team).

Frontier


An advance market commitment to accelerate carbon removal
Frontier is an advance market commitment to buy an initial $925M of permanent carbon removal between 2022 and 2030. It's funded by Stripe, Alphabet, Shopify, Meta, McKinsey, and tens of thousands of businesses using Stripe Climate.
Buyers
Get in touch →
Suppliers
Get in touch →
stripe
Alphabet
shopify
Meta
McKinsey & Company
How Frontier works
Frontier is an advance market commitment (AMC) that aims to accelerate the development of carbon removal technologies by guaranteeing future demand for them. The goal is to send a strong demand signal to researchers, entrepreneurs, and
The concept of an AMC is borrowed from vaccine development and was piloted a decade ago. The first AMC accelerated the development of pneumococcal vaccines for low-income countries, saving an estimated 700,000 lives.

Are you pro- or anti-nuclear?

Pro:

- Sepulveda et al 2018 make a convincing argument that it will be more expensive to achieve decarbonization without "firm" resources
- plenty of other reasons: land use!

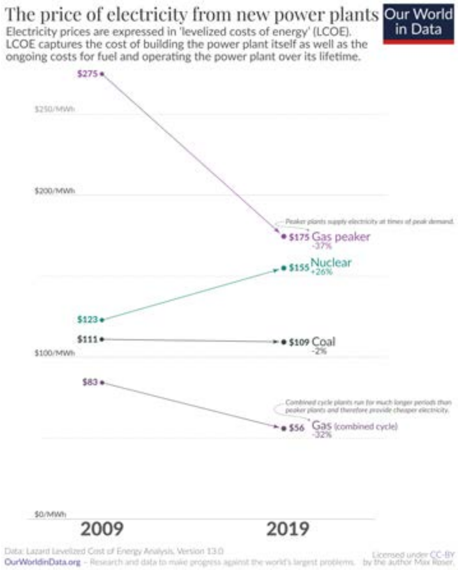
Cons:

- will it ever get cheaper?
- plenty of other reasons: nuclear waste! proliferation!

Perhaps a more useful way to think about it:

1. operating and maintaining the existing nuclear fleet (Lyman 2022, Diablo Canyon article)
2. building new nuclear with existing technology?
3. building new nuclear with new technology?

Figure courtesy of Our World in Data. License: CC BY.



From Our World in Data

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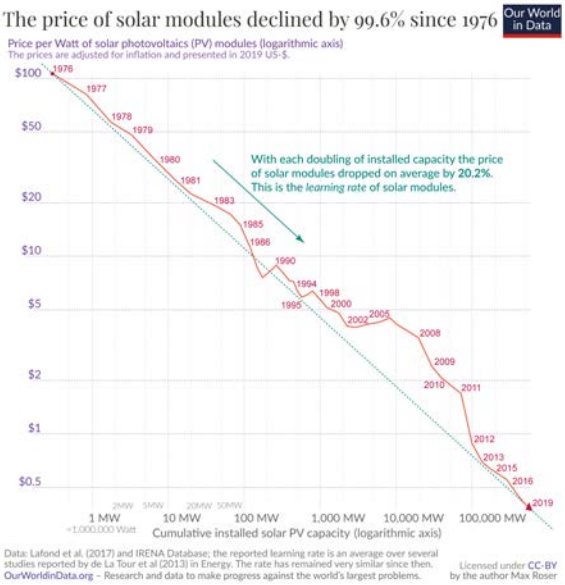

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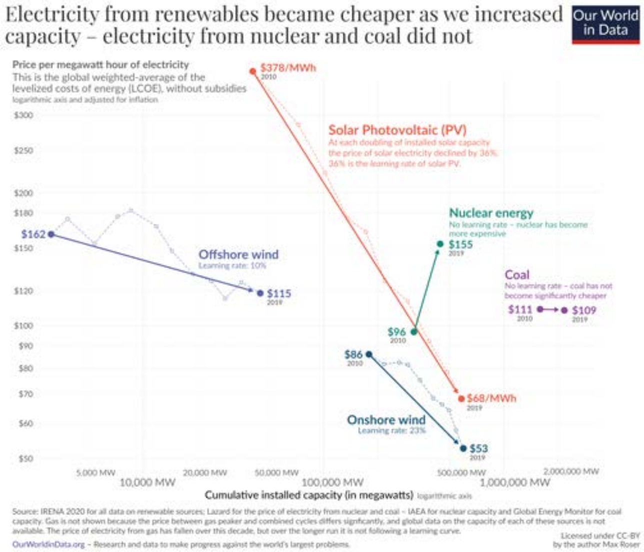

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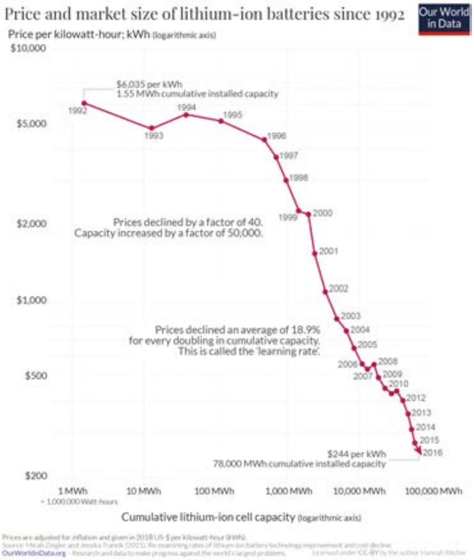


From Our World in Data

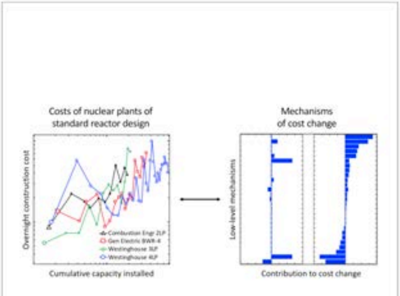
MIT 2020 paper on nuclear costs

Joule

CellPress

Article

Sources of Cost Overrun in Nuclear Power Plant Construction Call for a New Approach to Engineering Design



Philip Eash-Gates, Magdalena M. Klemun, Goksin Kavlak, James McNerney, Jacopo Buongiorno, Jessika E. Trancik

trancik@mit.edu

HIGHLIGHTS

US nuclear plant cost estimation does not align with observed experience

"Indirect" expenses, largely soft costs, contributed a majority of the cost rise

Safety-related factors were important but not the only driver of cost increases

MIT 2020 paper on nuclear costs

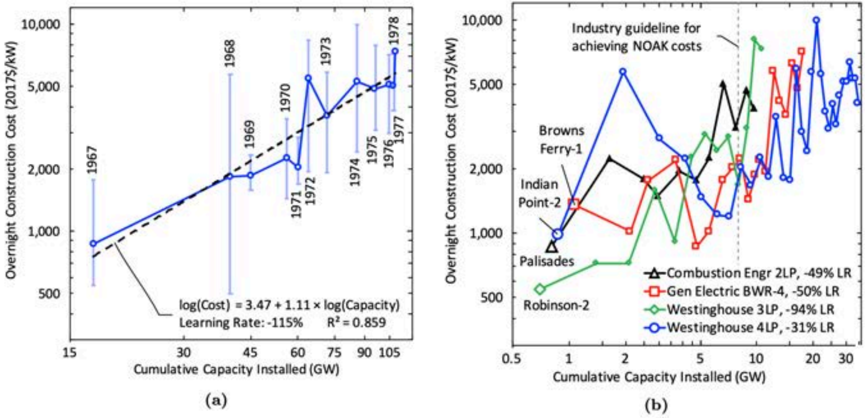


Figure 1: U.S. nuclear construction costs. (a) Average overnight cost of plants with construction beginning in each year from 1967 to 1978. Vertical bars give the minimum and maximum construction cost in each year. The dashed line is an OLS regression fit and its slope corresponds to a learning rate of -115%. (b) Overnight cost of individual plants for all four standard plant designs that reached a cumulative built capacity of 8GW$_e$ (indicated by the dashed vertical line), a threshold at which cost guidelines expect plants to realize NOAK cost reductions [14]. The first marker of each series shows the FOAK plant of a given design. OLS fits were made to the data for each plant design, from which the learning rates shown were computed.

MIT 2020 paper on nuclear costs

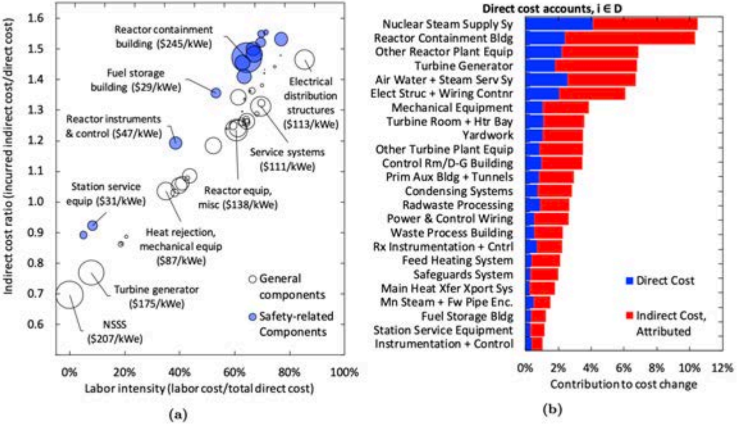


Figure 3: Nuclear plant indirect costs, 1987, and cost change, 1976-1987. (a) Attribution of indirect expenses to the direct cos accounts that incur them reveals that labor-intensive components and safety-related components represent a disproportionatel large share of indirect expenses relative to their cost. The containment building incurs more indirect expenses than any othe component. Results are shown for year 1987, though are similar in 1976; (b) Indirect cost accounts comprise 72% of th total cost change between 1976 and 1987. The containment building is responsible for the largest share of cost change due t indirect expenses. Only accounts with a cost change contribution exceeding 1% are included. Interest during construction i excluded. Abbreviations: Sy = system; Bldg = building; Equip = equipment; Serv = service; Rm = room; Prim = primary Aux = auxiliary; Xfer = transfer; Xport = export; Rx = reactor; D-G = diesel generator; Mn = main; Fw = feedwater; En = enclosure; Contnr = container; Htr = heater; Fac = facilities; Struc = structure; Temp = temporary.

French nuclear costs

Energy Policy
Volume 38, Issue 9, September 2010, Pages 5174-5188

The costs of the French nuclear scale-up: A case of negative learning by doing

Arnulf Grubler [a, b]

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Abstract

The paper reviews the history and the economics of the French PWR program, which is arguably the most successful nuclear-scale up experience in an industrialized country. Key to this success was a unique institutional framework that allowed for centralized decision making, a high degree of standardization, and regulatory stability, epitomized by comparatively short reactor construction times.

French nuclear costs

Drawing on largely unknown public records, the paper reveals for the first time both absolute as well as yearly and specific reactor costs and their evolution over time. Its most significant finding is that even this most successful nuclear scale-up was characterized by a substantial escalation of real-term construction costs. Conversely, operating costs have remained remarkably flat, despite lowered load factors resulting from the need for load modulation in a system where base-load nuclear power plants supply three quarters of electricity.

The French nuclear case illustrates the perils of the assumption of robust learning effects resulting in lowered costs over time in the scale-up of large-scale, complex new energy supply technologies. The uncertainties in anticipated learning effects of new technologies might be much larger that often assumed, including also cases of "negative learning" in which specific costs *increase* rather than decrease with accumulated experience.

Thank you!