Converting CO_2 into Products?

What's Up With That?

Sudhir Joshi, PhD
Faculty – Product Development Program
University of California Berkeley

What this talk is about?

What this talk is not –

- Evaluating business viability
- Commenting on success / failure in marketplace

What this talk is –

- $400+ M have been invested in start-ups that want to “add value” to CO_2
- **Does not pass the smell test**

- Show from first principles that these “solutions” will NOT reduce CO_2
- Suggest possible better alternatives to Founders and Funders alike

Conclusion

Best uses of renewable electricity are –

- Replacing coal → oil → NG generated electricity on the grid
- Replacing ICE vehicles with EV's

As long as there is "dirty electricity" and ICE vehicles –

- Trying to convert CO_2 to either chemical or food does more harm than good
- Trying to capture CO_2 does more harm than good
- It wastes precious resources and time on distractions

Who is the audience?

Founders & Funders who are seeking REAL climate change solutions

Govt. agencies that provide early funding

Climate Policy Makers

If you disagree …

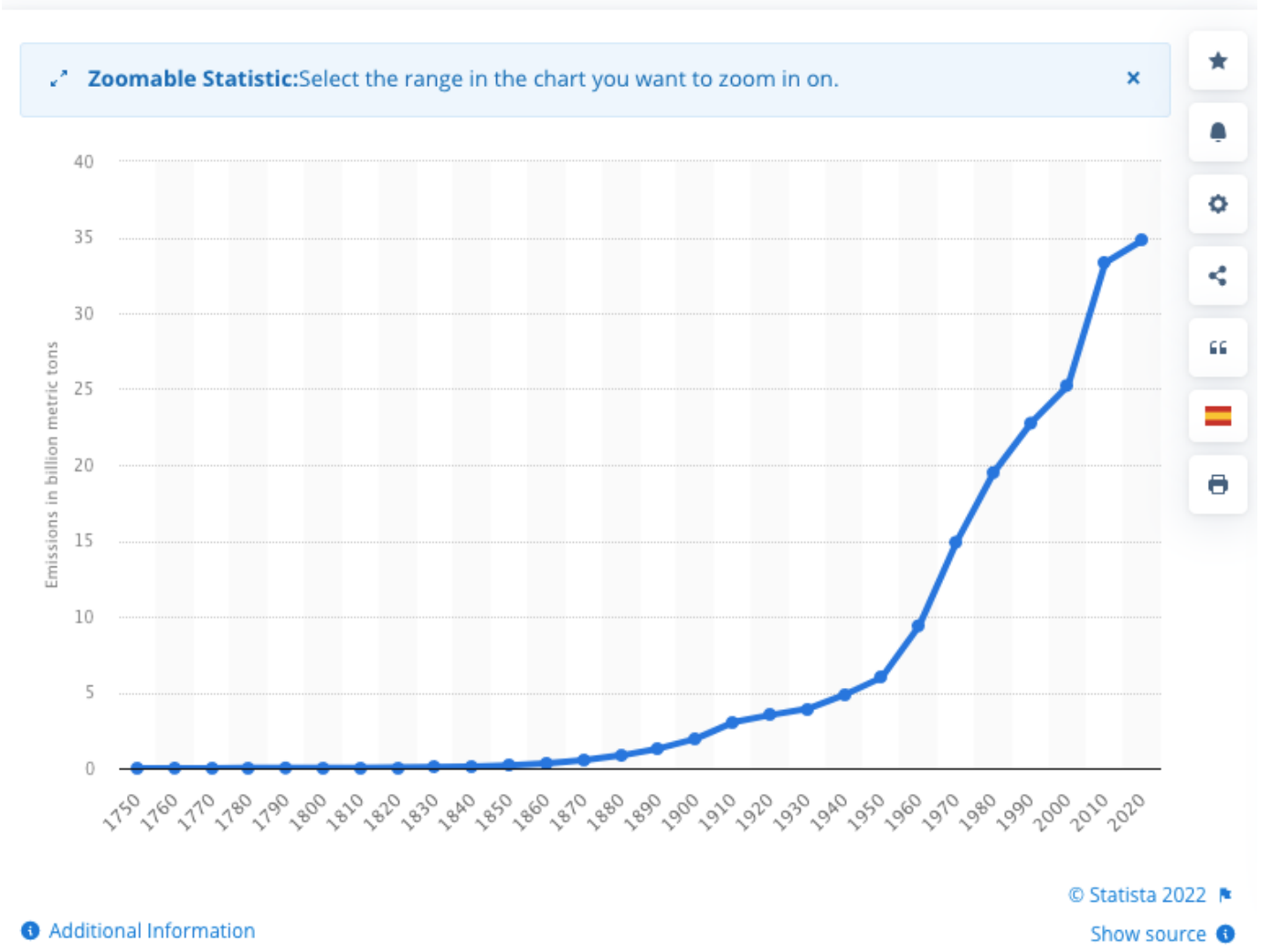
If you are a founder or a funder of either a CO_2 capture company or a CO_2 to chemical / food company and disagree with my analysis,

- **I would like to hear from you**
- **If I am wrong, I will do another talk and correct any mistakes**
- **I will also buy you a cup of coffee next time you visit SF Bay Area**

Sudhir Joshi
sudhirjoshi@berkeley.edu
650-556-3835

What is the problem?

- CO2 emitted since the Industrial Revolution (Ca. 1750 – today)
  - ~ 900 - 1000 B MT
  - Powered our civilization for over 250 years



What is the problem?

Let's start from 1st principles

- CO_2 is the lowest energy state of carbon (except for CO_3^{-2})
- Upcycling CO_2 has unfavorable ΔH & ΔG

Thermodynamics dictates that upcycling of CO_2

- Will require more energy than was extracted
- Part of the energy must be in the form of Work

Food from CO_2 … Huh?

air protein.

Making Air Meat Our Story Join the Team C

Meat Made From Air

LIBERATING PROTEIN PRODUCTION

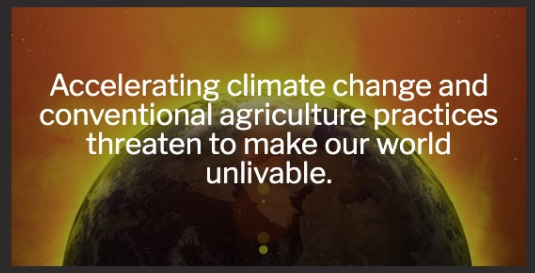
At Solar Foods, we've created a revolutionary way to produce a natural protein with just electricity and air. An entirely new kind of food that is natural, can taste like anything, and unlike any other food, not limited to the availability of land or the use of animals, agriculture and aquaculture.

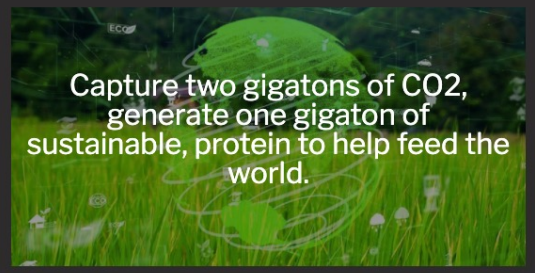
The liberation of protein production is finally possible.

See the impact we can make »

Liberating protein production.

SOLAR FOODS





NovoNutrients cleanly upcycles carbon dioxide into alternative protein ingredients.

Our process utilizes natural microbes to ferment emissions gases.

We combine sustainable bioprocessing, carbon capture utilization, and renewable energy to help the world eat better and mitigate climate change.

Deep Branch®

About Us Platform

Alternative Protein, Simplified

Harnessing the power of microbes, Deep Branch's proprietary **CO_2-to-protein** platform converts clean carbon dioxide and hydrogen into high-quality ingredients to support a more sustainable food system. **Proton™**, a single-cell protein, is optimized for animal nutrition.

Who are these companies?

4 Leading companies have raised combined ~ $ 90M
(Per Pitchbook)

- Solar Foods $ 38M
- Air Protein $ 32M
- Novo Nutrients $ 10M
- Deep Branch $ 10M

There may be other companies in early stages

Food from CO_2 … What they claim

- Make protein-rich microbial biomass
- Using only CO_2, renewable electricity, water (some also use H_2)
- Requires lot less water and land

NovoNutrients cleanly upcycles carbon dioxide into alternative protein ingredients.

Our process utilizes natural microbes to ferment emissions gases.

We combine sustainable bioprocessing, carbon capture utilization, and renewable energy to help the world eat better and mitigate climate change.

Start With Elements of the Air

Air fermentation begins with the same building blocks that all plant life needs to grow–air, water, and renewable energy.

Harnessing the power of microbes, Deep Branch's proprietary **CO_2-to-protein** platform converts clean carbon dioxide and hydrogen into high-quality ingredients to support a more sustainable food system. **Proton™**, a single-cell protein, is optimized for animal nutrition.

At Solar Foods, we've created a revolutionary way to produce a natural protein with just electricity and air. An entirely new kind of food that is natural, can taste like anything, and unlike any other food, not limited to the availability of land or the use of animals, agriculture and aquaculture.

Food from CO_2 … Let's unpack

- Use fast microbial fermentation to convert CO_2 into edible biomass
- Isolate protein OR use whole biomass
- Resulting product is like flour but higher protein
- Further processed into meat analogue OR sold as ingredient
- End Product: Food or Animal feed

Food from CO_2 … Analysis Method

- Process details are proprietary
- Customers, economics, and business models unknowable
- We will focus on:

Is this truly carbon negative?
Is this the best use of renewable electricity?

- We will use a paper by Dr. Silman
- Determine best use for electricity

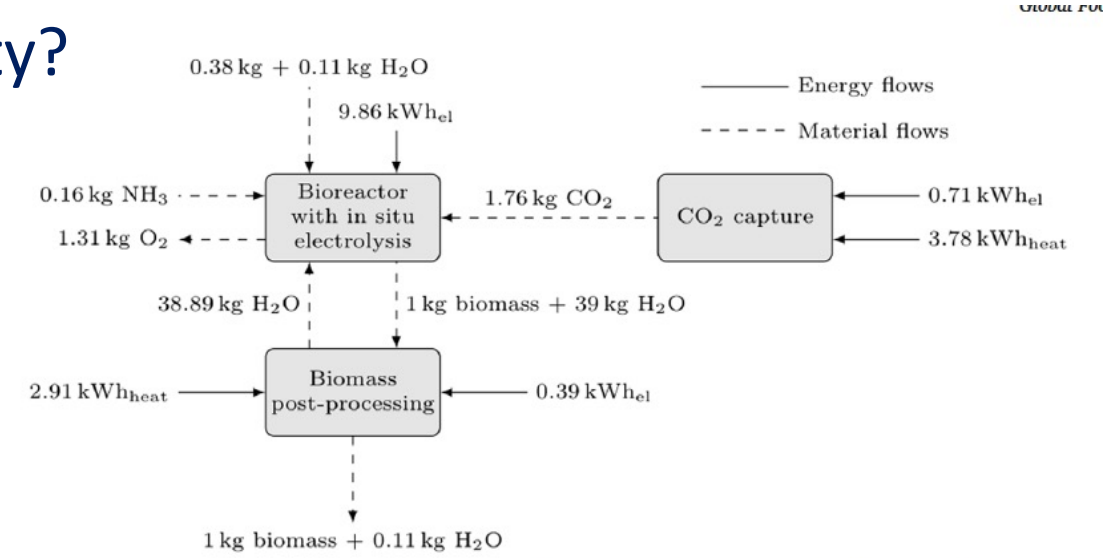


Fig. 3. Approximated main material and energy flows required to produce 1 kg of bacterial biomass.

Silman, J, et. Al. Global Food Security 22 (2019) 25-32

Silman paper – high level takeaway

3.87 lbs of CO2 + 13.2 kWh electricity → ~ 1 lb of protein

(1 Kg biomass @ 65% dry mass, 75% protein = ~ 1 lb protein)

- If electricity is renewable, the process should be carbon neutral

  (Since it's turning into food, it would eventually be released. So I will call it neutral)

Food from CO_2 – Let's unpack

3.87 lbs of CO2 + 13.2 kWh electricity → ~ 1 lb of protein

- CO2 intensity of fossil fuel electricity in the US – (EIA 2021)
  - From coal – 2.23 lbs/kWh
  - From nat. gas – 0.91 lbs/kWh
  - Grid average – 0.99 lbs/kWh

What if …
we use those 13.2 kWh to replace dirty electricity?

- **From coal – Save 29 lbs of CO_2 releases (7.5x)**
- **From nat. gas – Save 12 lbs of CO_2 releases (3x)**
- **Grid average – Save 13 lbs of CO_2 releases (3.3x)**

How you define system/environment matters

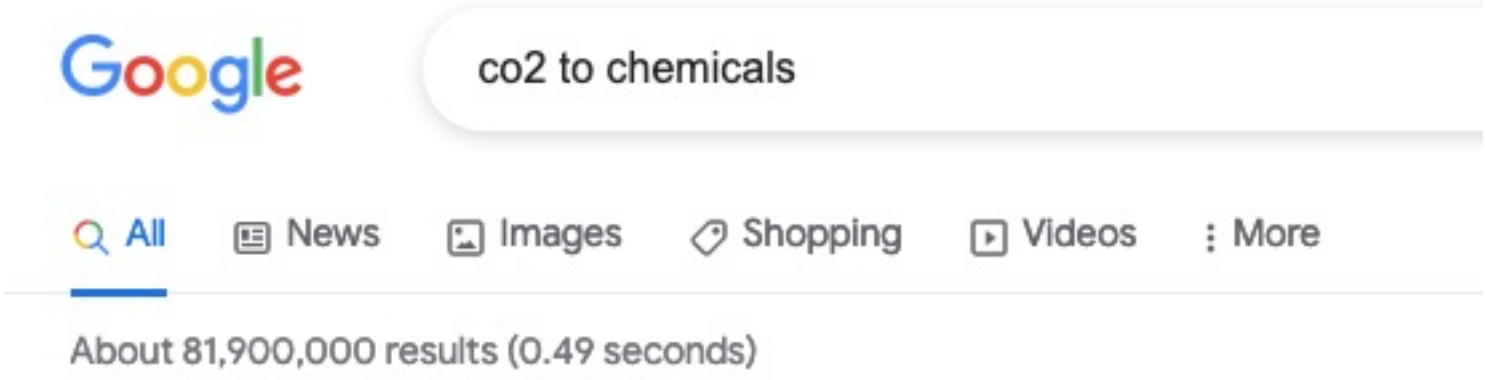
(As defined for thermodynamic analysis)

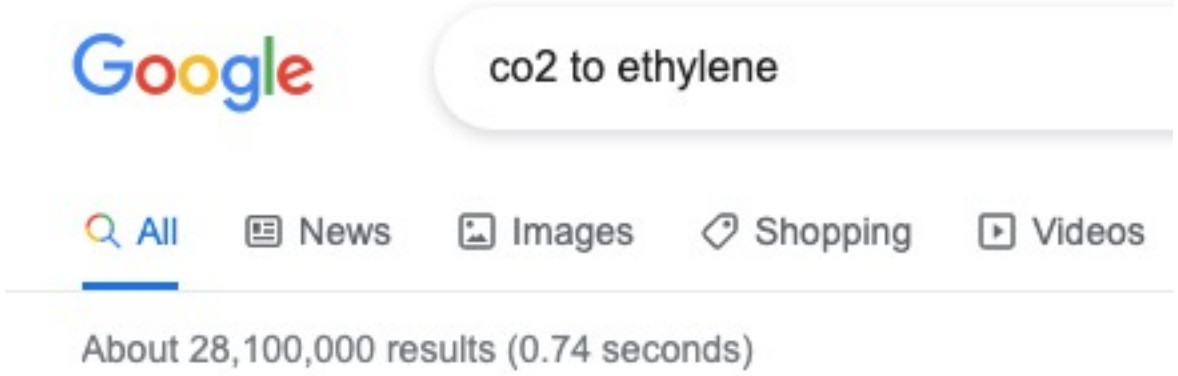
- In the previous example, if comparison is done in isolation
  - Process should be CO_2 negative
  - BUT that is a false narrative

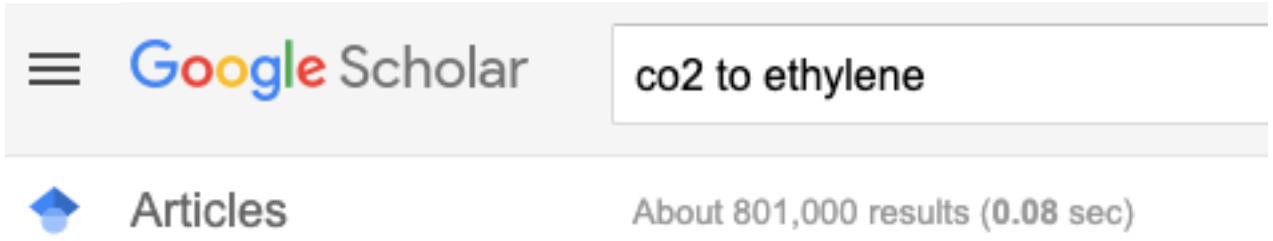
- Renewable electricity is a constrained resource
- CO_2 in the air is not contained. It travels everywhere.
- So we must take a global view

- **Missed Opportunity Cost is higher than selected option**

Chemicals from CO_2 … Is it a thing?







Stanford | News

Search Stanford news...

Home Find Stories For Journalists Contact

FEBRUARY 9, 2022

Stanford engineers create a catalyst that can turn carbon dioxide into gasoline 1,000 times more efficiently

KPMG

Insights Industries Services Client Stories

Turning CO2 into a business opportunity

Manufacturing CO2-based chemicals through CCU is becoming an increasingly competitive and attractive business prospect. Here's why.

Home › Insights › Turning CO2 into a business opportunity

MIT News

ON CAMPUS AND AROUND THE WORLD

SUBSCRIBE

Overcoming a bottleneck in carbon dioxide conversion

Study reveals why some attempts to convert the greenhouse gas into fuel have failed, and offers possible solutions.

David Chandler | MIT News Office
January 11, 2022

Chemicals from CO_2 … Is it a thing?

Who are these companies?

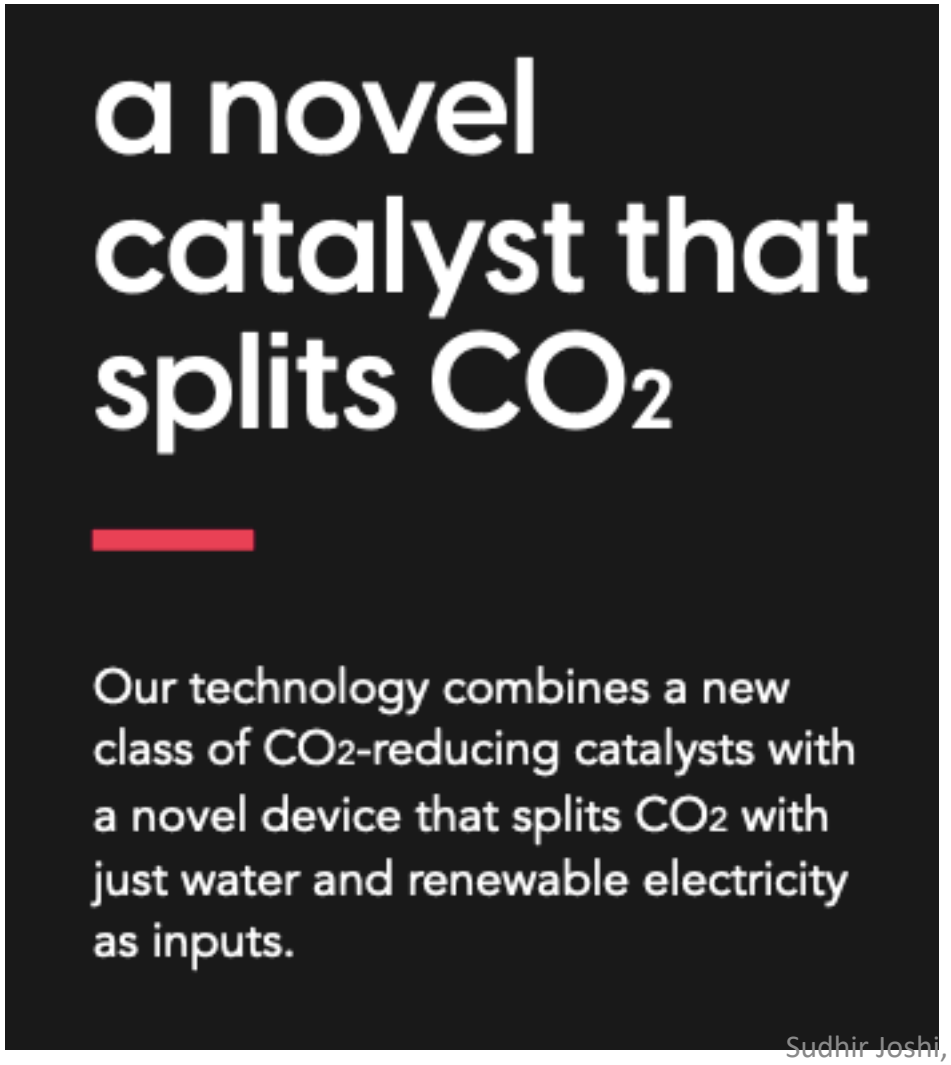
TWELVE (formerly Opus 12) – $64M
Prometheus – $13M
Cool Planet – $170M
ReCarbon – $7M

There are many other

We will look at TWELVE (not picking on them)

- They have a good website
- They specify to make ethylene

What TWELVE claims?



CO_2 to ethylene? … Let's unpack

CO_2 → C_2H_4 Using renewable electricity

- We don't know process details and efficiencies, assume ideal case, 100% efficient

$$2CO_2 + 2H_2O \rightarrow C_2H_4 + 3O_2 \quad \Delta H_R = +370 \text{ Wh}^*$$

- Make 1 lb C_2H_4 – Consume 3.1 lb CO_2 – Use 6 kWh of renewable electricity
- Looks carbon negative

* Kotaro Ogura, J. CO2 Utilization 1(2013) 43-49

CO_2 to ethylene? … Let's unpack

Make 1 lb C_2H_4 – Consume 3.1 lbs CO_2 – Use 6 kWh of renewable electricity

Using carbon intensity data from EIA,

6 kWh of RE if used on the grid;

- **From coal – Save 13.2 lbs of CO_2 releases (4.25x)**
- **From nat. gas – Save 5.5 lbs of CO_2 releases (1.8x)**

Remember we assumed 100% conversion and 100% efficiency.

* Kotaro Ogura, J. CO2 Utilization 1(2013) 43-49
** EIA

But you say, we didn’t make any ethylene?

Which is a better way to make ethylene?

Pappijn et al.

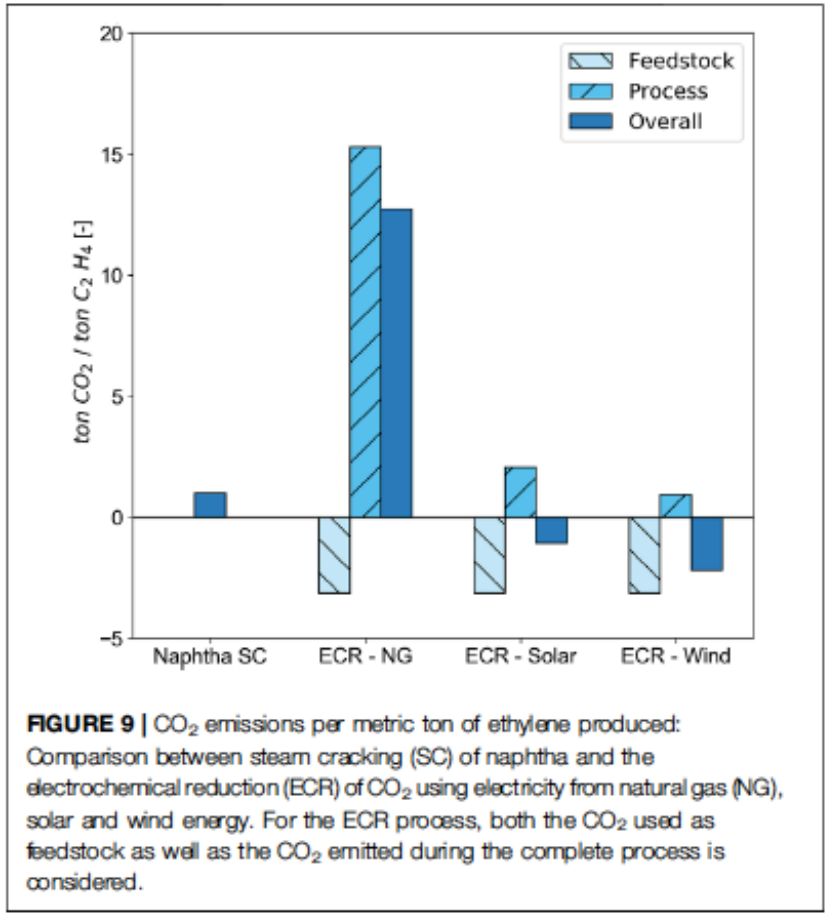


FIGURE 9 | CO_2 emissions per metric ton of ethylene produced: Comparison between steam cracking (SC) of naphtha and the electrochemical reduction (ECR) of CO_2 using electricity from natural gas (NG), solar and wind energy. For the ECR process, both the CO_2 used as feedstock as well as the CO_2 emitted during the complete process is considered.

Assumes Ideal Electrolyzer –
100% conversion & selectivity

C2H4 – 1 MT
CO2 – (-) 3.14 MT
Electricity – 10 MWh

10MWh of grid electricity
Coal – Add 10 MT of CO_2
NG – Add 4.2 MT of CO_2

Source: Pappijn, C.; et. al., Front. Energy Res., 28 Sep. 2020 https://doi.org/10.3389/fenrg.2020.557466)

Which is a better way to make ethylene?

Pappijn et al.

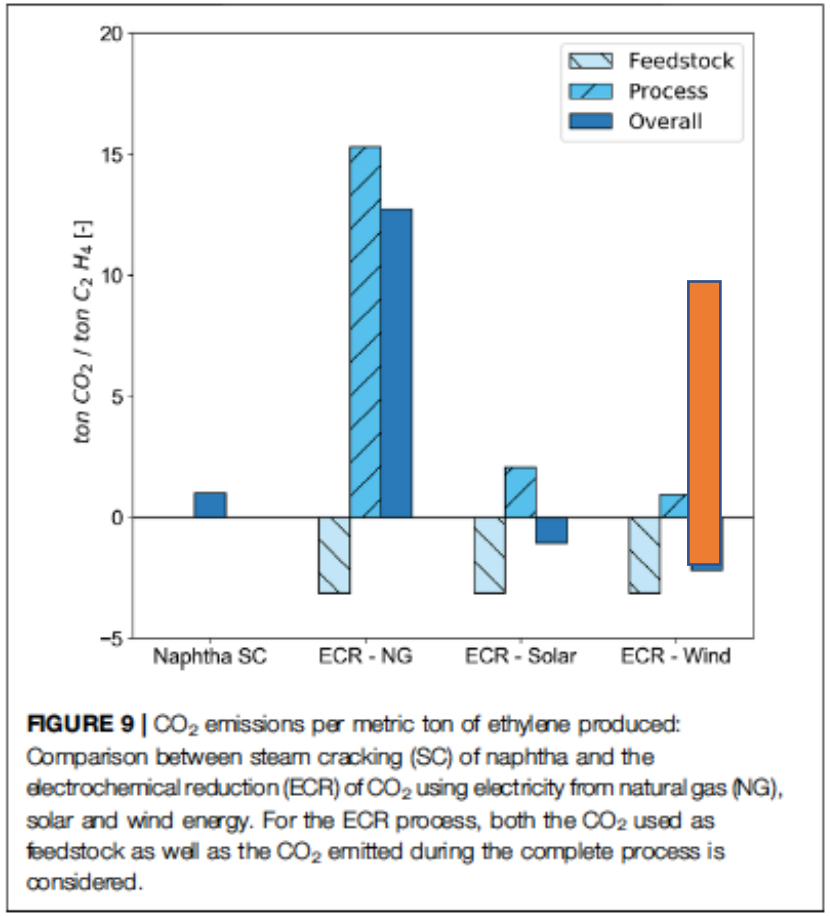


FIGURE 9 | CO_2 emissions per metric ton of ethylene produced: Comparison between steam cracking (SC) of naphtha and the electrochemical reduction (ECR) of CO_2 using electricity from natural gas (NG), solar and wind energy. For the ECR process, both the CO_2 used as feedstock as well as the CO_2 emitted during the complete process is considered.

Assumes Ideal Electrolyzer –
100% conversion & selectivity

C2H4 – 1 MT
CO2 – (-) 3.14 MT
Electricity – 10 MWh

10MWh of grid electricity
Coal – Add 10 MT of CO_2
NG – Add 4.2 MT of CO_2

Source: Pappijn, C.; et. al., Front. Energy Res., 28 Sep. 2020 https://doi.org/10.3389/fenrg.2020.557466)

Which is a better way to make ethylene?

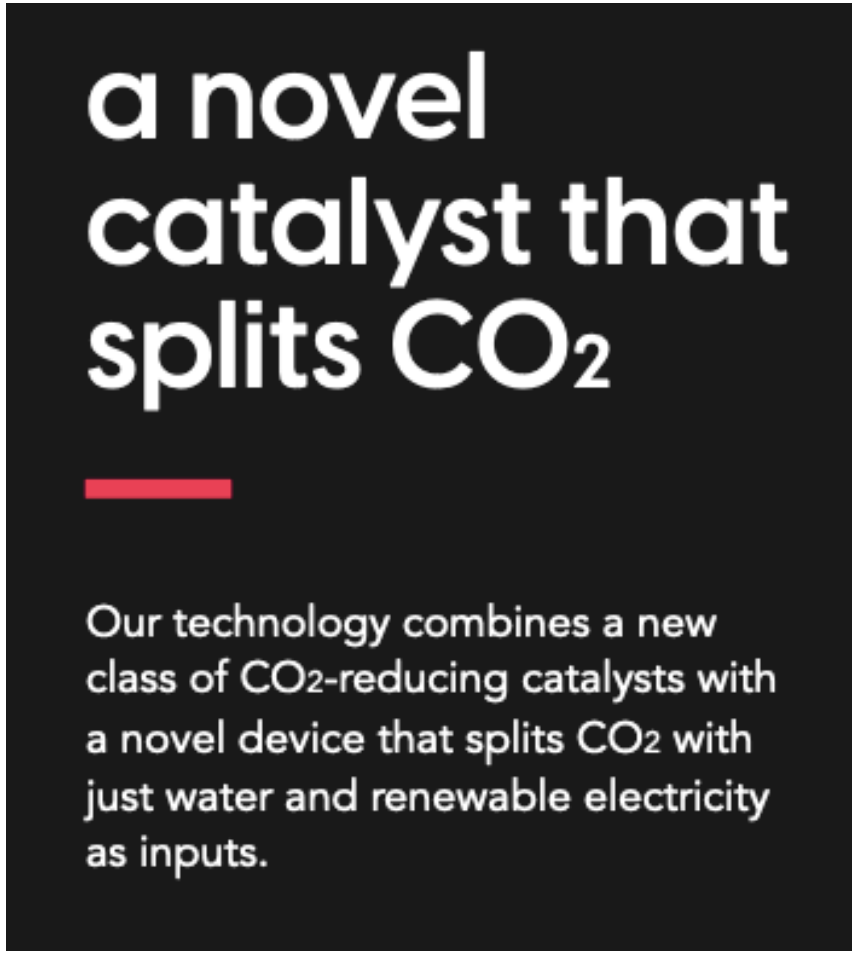
- CO_2 → Ethylene options
- (Source: Pappijn, C.; et. al., Front. Energy Res., 28 Sep. 2020 https://doi.org/10.3389/fenrg.2020.557466)
- 1 MWh of electricity produces 0.032 MT C_2H_4 via electrochemical reduction of CO_2
- Basis: We want to make 0.032 MT C_2H_4
- We have: 1 MWh of clean electricity
- 1 MWh of coal produced electricity
- Existing Ethylene cracker
- What is the best way to make 0.032 MT C_2H_4 that produces the least CO_2?

	Option 1 Use clean electricity (CE) to make C_2H_4 Use coal generated electricity on grid Leave thermal cracker unused	Option 2 Use thermal cracker to make C_2H_4 Clean electricity replaces coal electricity Coal plant make 1 MWh less
C_2H_4 produced	0.032 MT	0.032 MT
CE makes C_2H_4	Consume net 0.07 MT CO_2	
CE to grid	None	1 MWh + zero CO_2
Coal electricity to grid	1 MWh + Releases 1.0 MT CO_2	None
Thermal cracker	Idle	Releases 0.058 MT CO_2
End result		
C_2H_4 produced	0.032 MT	0.032 MT
CO_2 emitted	0.93 MT	0.058 MT
	16 X more	

Ranking of CO2 Mitigation Schemes using renewable power

(J. Lattner, "Current Opinion in Chemical Engineering", 2020, 29:51-58, Table 2)
Edited for brevity

CO2 Mitigation Scheme Renewable power -	g CO2 mitigated per MJ electric power	Ratio
Displaces coal fired plant	291	5.7
Grid to BEV to replace gasoline car	189	3.7
Displaces NG fired open cycle plant	141	2.8
Electrolysis of water to H2 for FCV to replace gasoline car	103	2.0
Displaces NG fired combined cycle plant	99	1.9
Direct electrolysis of CO2 to methanol as fuel in IC car	64	1.3
Water to H2, combine with CO2 to methanol as fuel in IC car	51	1.0



We just showed that it's not about the kinetics but about Rxn Thermodynamics

There's no escape from Thermo

"Moore's Law" does not apply in this case

Fuels from CO_2 … Is it a thing?

Making larger fuel molecules will be even more difficult and less efficient

How you define system/environment matters

(As defined for thermodynamic analysis)

- In the previous example, if comparison is done in isolation
  - Process should be CO_2 negative
  - BUT that is a false narrative

- Renewable electricity is a constrained resource
- CO_2 in the air is not contained. I travels everywhere.
- So we must take a global view

- **Missed Opportunity Cost is higher than selected option**

Carbon Capture

- Before one can ”add value to CO_2”, it must be captured
- Literature data is all over the place.
- Carbon Engineering* reported actual number for DAC
  - 8.8 GJ/MT CO2 = ~ 1.1 kWh/lb of CO_2
  - That is more than generated by NG power plant but less than coal fired power plant
  - The reported number is ~ 8x of theoretical minimum**

This energy penalty must be added before any “value add”

* https://www.rechargenews.com/energy-transition/the-amount-of-energy-required-by-direct-air-carbon-capture-proves-it-is-an-exercise-in-futility/2-1-1067588

** *SAPEA, Science Advice for Policy by European Academies. (2018)*

Carbon Price / Carbon Tax

- Carbon price or tax is a complex issue
- Not sure if it will ever happen and how the market will react if it does happen

BUT

- Any carbon tax or price will negatively impact access to renewable electricity (RE)
- RE provider would get higher benefit by
  - Replacing fossil fuel generated electricity
  - Selling power to clients looking for offsets

If you are working on “adding value to CO_2”

Some Possible Alternatives

You want to help w/ climate change. What should you do?

Obvious (Many current players)

- More energy dense and cheaper batteries for EV's
- Practical cheap batteries for stationary storage
- More efficient solar with much higher than today
- Solar that can harness wider wavelength band
- Stronger and recyclable wind turbine blades
- Cheaper more efficient wind turbines
- Greener way of making cement or reducing usage of cement
- More efficient green H_2
- Energy storage as heat or chemical energy
- 100% reliable way to eliminate peaker plants
- More resilient grid with much higher capacity

You want to help w/ climate change. What should you do?

Not so obvious (needs major innovation in technology and business models)

- On-site on-demand nitrogen fertilizer using solar only (Nitricity)
- Row crops that capture their own N (Pivot Bio)
- Certifiable long-term carbon capture by forests (Pachama)
- Certifiable long-term carbon capture by farmland & prairies (?)
- Better meat substitutes that drastically reduces meat consumption, stopping rain forest loss and monetizing that reduction
- Regeneration of rain forests and monetization
- Regenerative agriculture and monetization
- Genetic modification to increase photosynthesis efficiency
- Replace steel with wood in < 5 story buildings
- Rapid and inexpensive way to plant trees – right tree and other vegetation at right place (Dendra Systems, Droneseed)
- Highly efficient HVAC's to reduce electric usage for cooling

You want to help w/ climate change. What should you do?

Wilder Ideas

- Genetically modified algae, plankton or bacteria that speed-up carbon capture or speed up exuded biopolymers that sink
- Treated municipal water reuse. Can it be used to grow vegetation to store CO_2?
- Paints that reflect most of incident sunlight (reduce cooling)
- Regenerative agriculture with multiple simultaneous crops
- Perennial cereal crops
- Implanted male contraception
- Better education in developing world especially for girls/women (to reduce population growth)
- More efficient air and sea transport
- Reforestation

Thank You