


Synthetic Fuels - Opportunities and Challenges Spanning Biomass, e-Fuels, and Solar Fuels

Randy Cortright, Senior Research Advisor

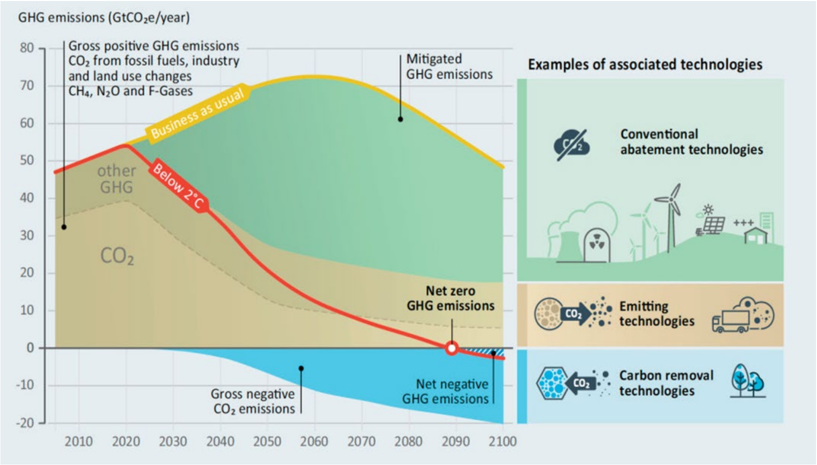
Zia Abdullah, Biomass Laboratory Program Manager

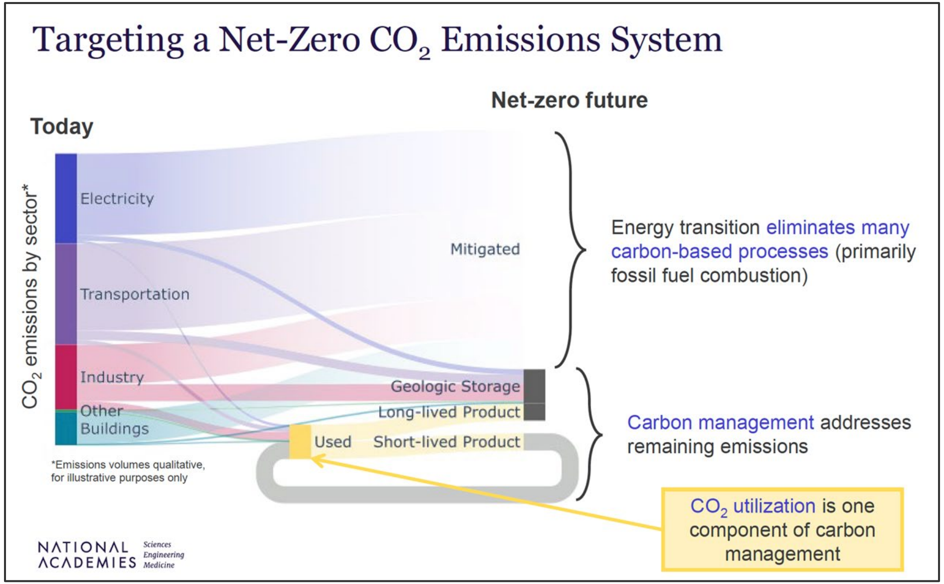
Bill Tumas, Associate Lab Director

September 30, 2025

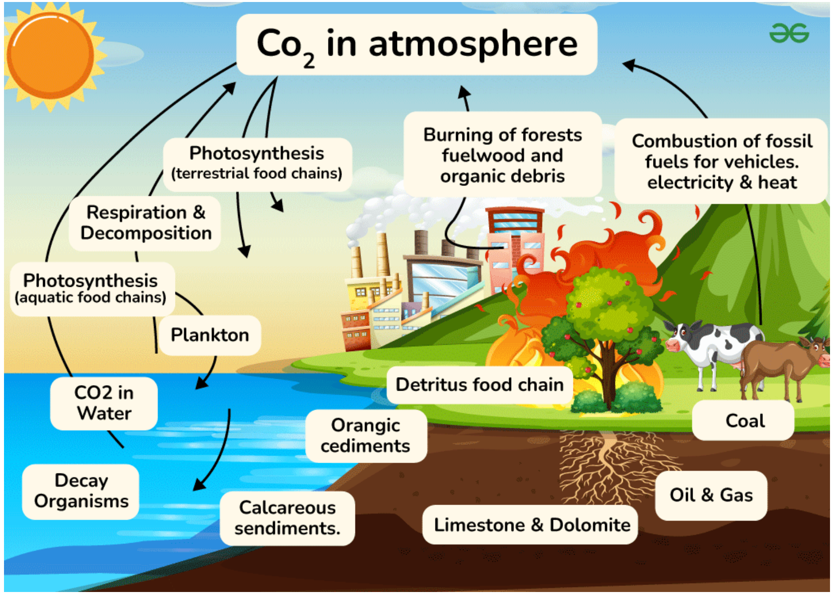
Strategy for CO2 Emissions

- Eliminate CO2 emissions through energy transition (electrification)
- Utilize Carbon Management Technologies to address remaining emissions
- Carbon Dioxide Removal (CDR) for rolling back atmospheric CO2 Concentrations

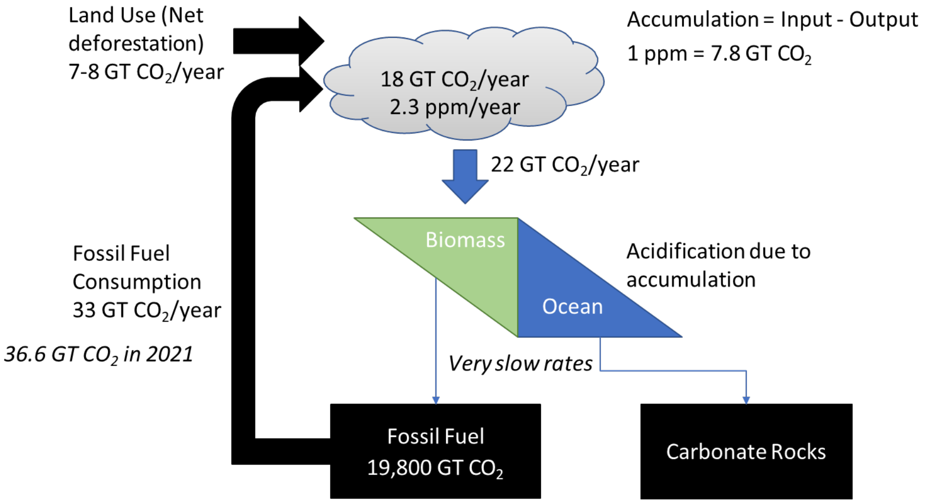




Carbon Cycle



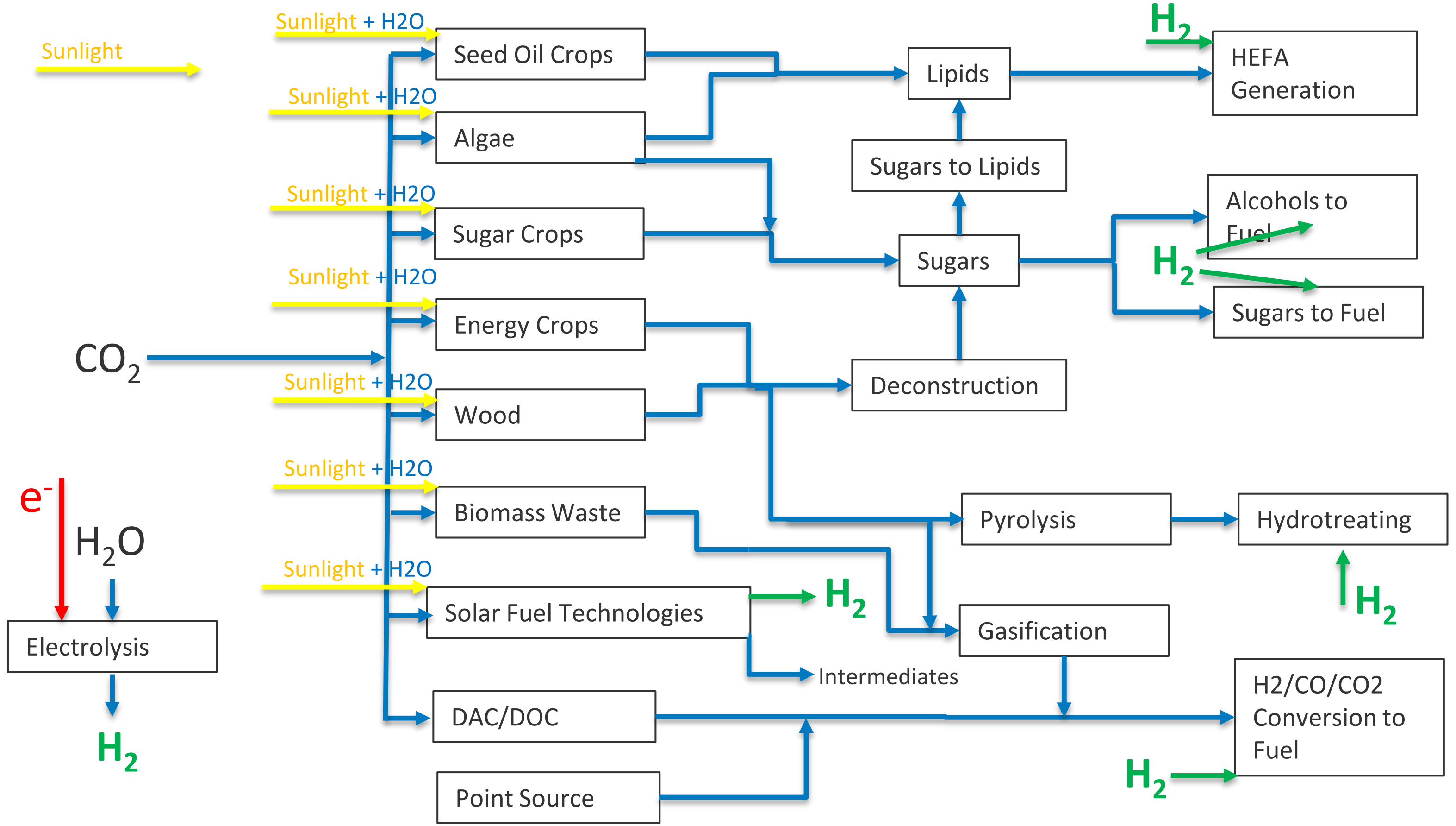
The Global Carbon Cycle



Rate of release exceeds the earth systems' capacity to absorb.

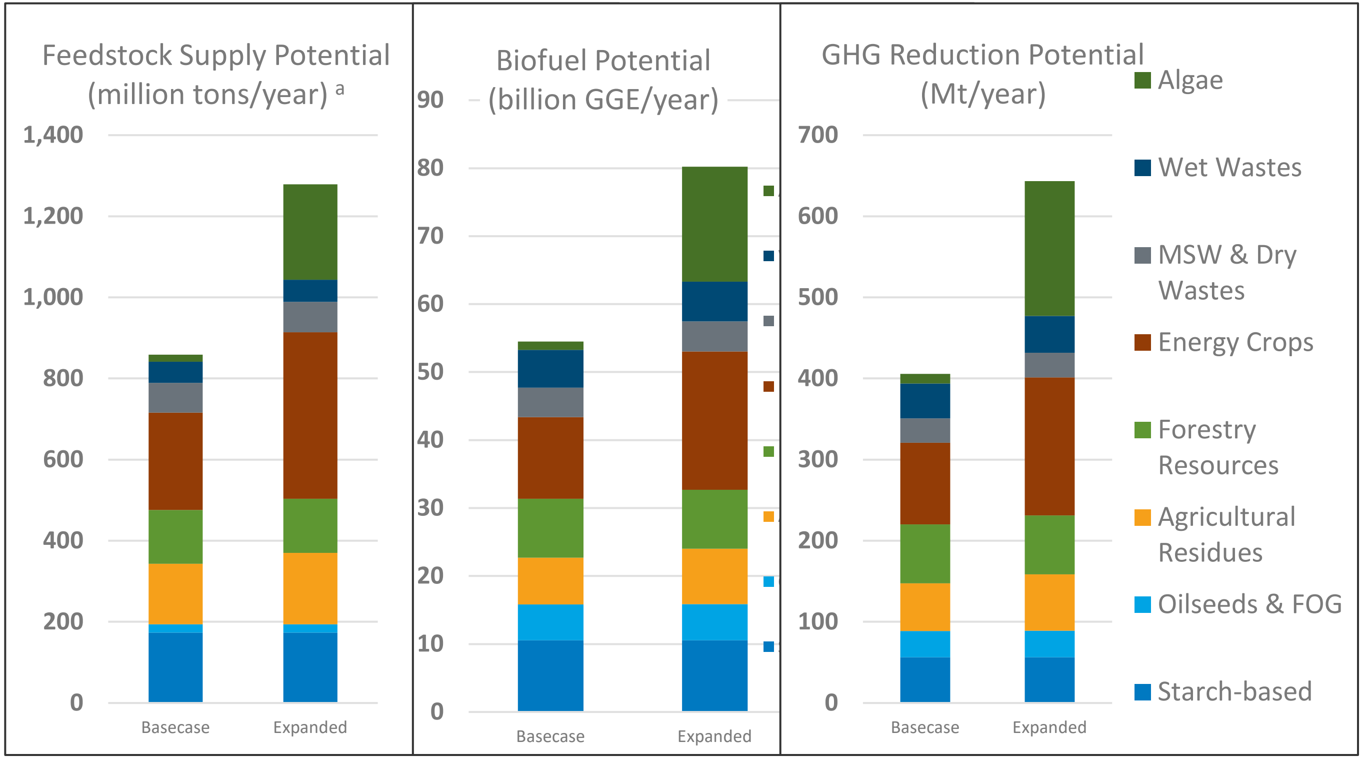
MJ Realff, P Eisenberger, Flawed analysis of the possibility of air capture. Proc Natl Acad Sci USA 109, E1589 (2012)

Sustainable Fuel Roadmap



US Biomass Feedstock Supply and Biofuel Potential

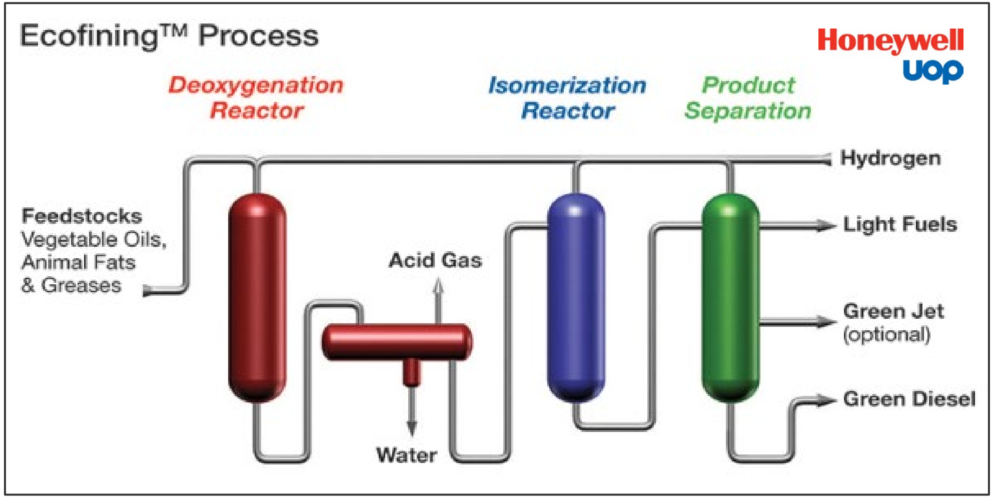
- Carbon feedstocks
  - 858 to 1,279 million tons/yr.
- Fuel production
  - 55 to 80 billion GGE/yr.
  - US Fuel Consumption is 220 billion gallons
- Total GHG emissions saving
  - 406 to 644 million tons/yr.

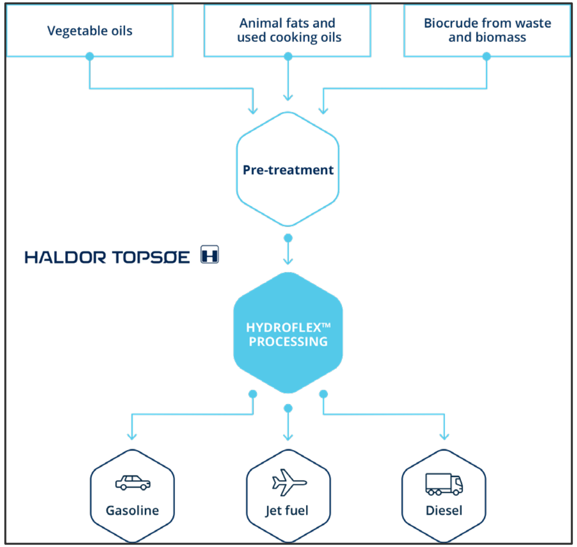


[a] Dry and wet waste feedstocks are reported on a dry basis. Algae is reported on an AFDW dry basis. Starch-based, oilseed, and waste FOG are reported on an as-received basis.

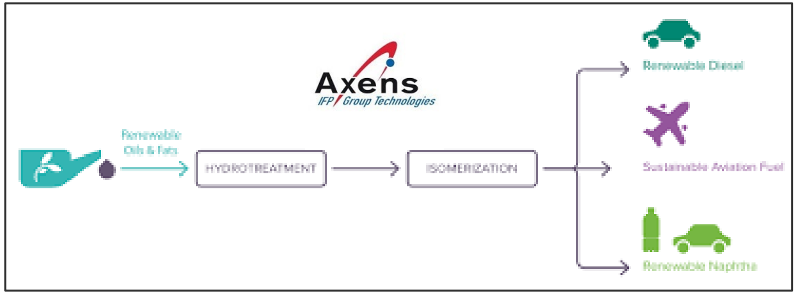
Source: https://www.osti.gov/biblio/2202642

Renewable Diesel and Sustainable Jet Fuel from Lipid Feedstocks





NESTE MY
Sustainable Aviation Fuel



Leveraging Petroleum Industry's $10B Investment in Hydrotreating Will Lower Costs and Accelerate Deployment

Opportunities to Use Existing Petroleum Refineries

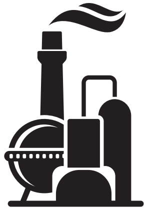
- US has ~6.6M BBPD (97 BGPY) distillate hydrotreatment and finishing capacity
- Much of this capability is already depreciated
- This capability may become idled with electrification of ground transportation

Opportunity

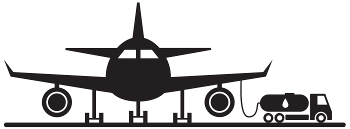
Leverage ~$10B of depreciated capital equipment by pretreating renewable streams so that they can be processed by refinery hydrotreatment equipment

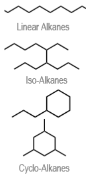
Fats, Oils, Greases
FT Waxes & Oils
Alcohols
Bio-Oils/Biocrudes
Ketones
Sugars
Algae Oils
Lignins

Pretreatment of Feeds to Meet Critical Material Attributes (CMA)



Petroleum Refinery
- Hydrotreatment
- Fuel finishing
- Trained workforce
- Industry know-how



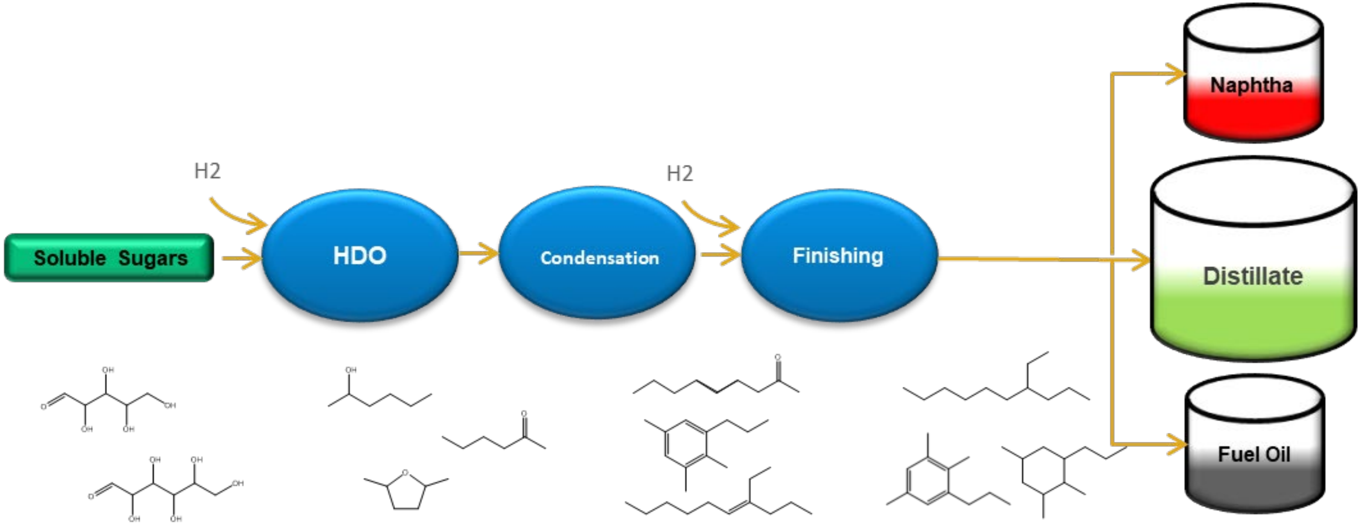


- Fuel QA/QC
- Fuel delivery
- Fuel branding

Critical Material Attributes (CMA)
- These are physical and chemical properties of pretreated renewable streams which can be processed by refineries with no or minor modifications

https://www.eia.gov/dnav/pet/PET_PNP_CAP1_A_(NA)_8CDHD0_BPSD_A.htm

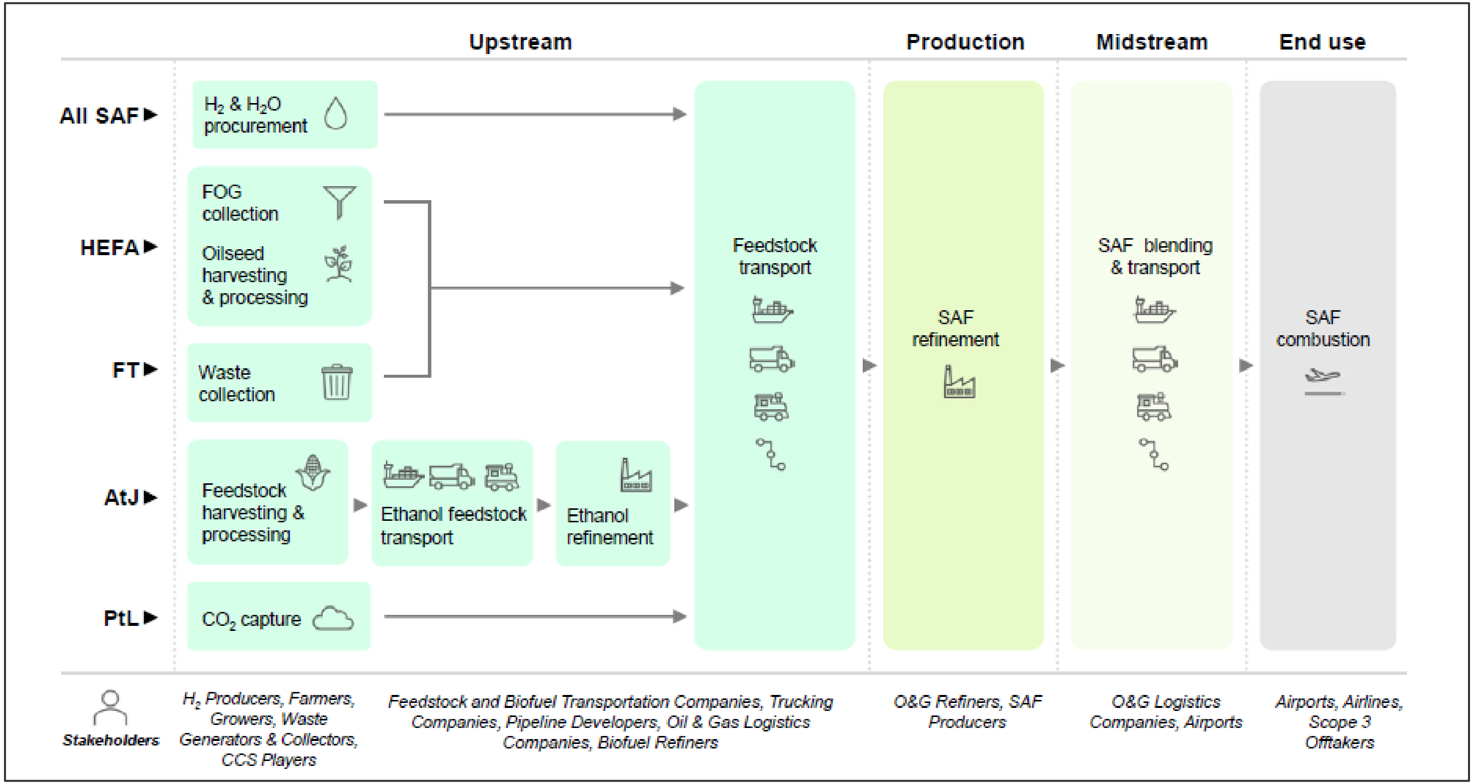
Virent's BioForming® Distillate Process Chemistry



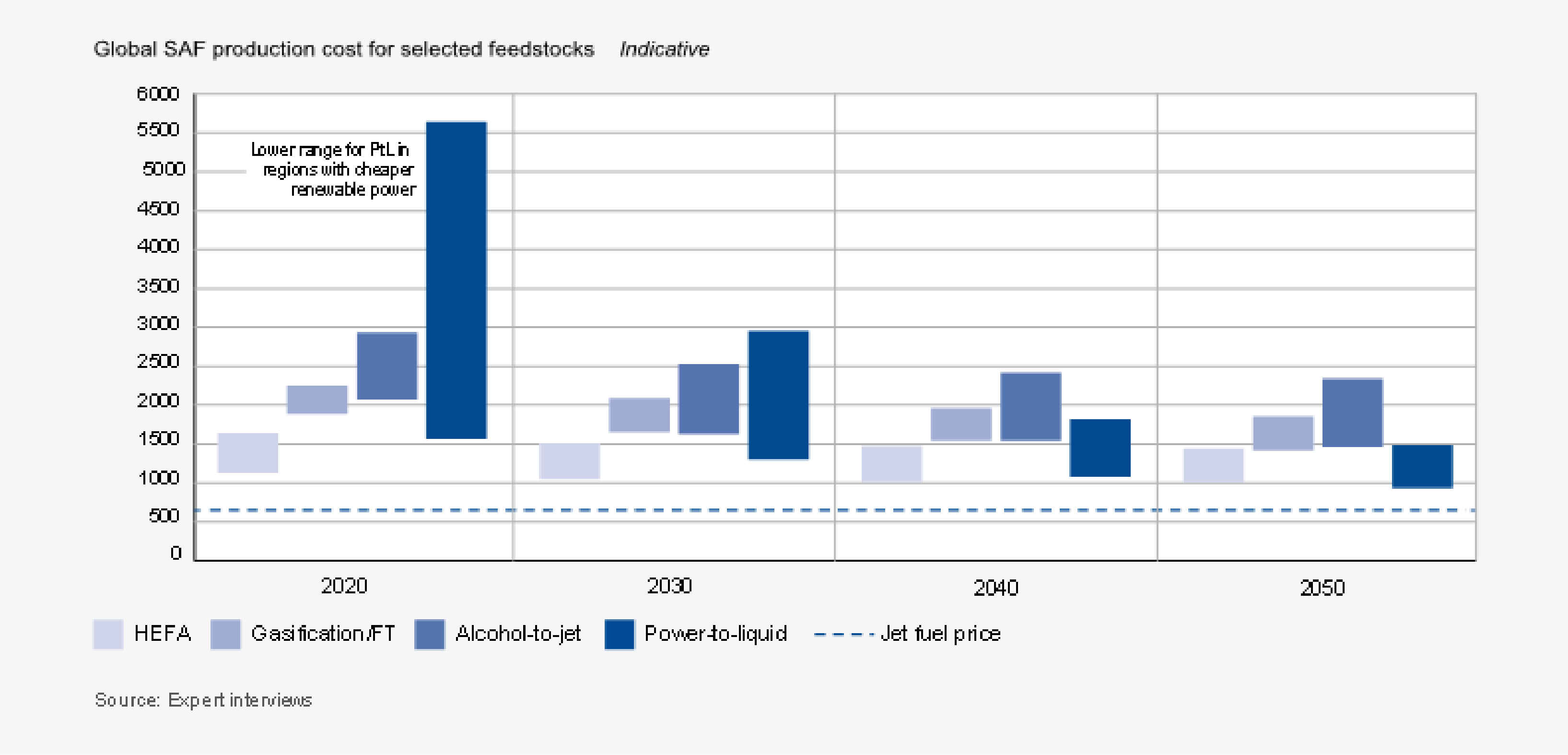
Reactive Oxygenates	Moderate Functionality Controlled Reactivity Oxygenates	Low Functionality Hydrocarbons and Residual Oxygenates	Hydrocarbons
Sugars, Oligosaccharides, Polyols, Furans	*Alcohols, Ketones, Furans, Carboxylic Acids*	*Olefins, Paraffins, Aromatics, Ketones, Esters*	*Paraffins,Cycloparaffins, Aromatics*
Carbon Chain Length ≤ 6	Carbon Chain Length ≤ 6	Carbon Chain Length 4-40	Carbon Chain Length 4-40
2-6 Oxygen/Carbon Chain	1-3 Oxygen/Carbon Chain	0-1 Oxygen/Carbon Chain	0 Oxygen/Carbon Chain

US Patents 9,944,869, 9,593,054, 9,228,134, 9,217,114, 9,206,366, 8,933,281, 8,455,705, 8,367,882, 8,362,307, 8,053,015, 8,017,818, 7,977,517

Pathways to Commercial Liftoff: Sustainable Aviation Fuel (DOE Report: November 2024)



Transition of Sources of SAF



World Economic Forum in Collaboration with McKinsey & Company
Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net Zero Aviation
November 2020

Early Market Driver (SAF in the EU)

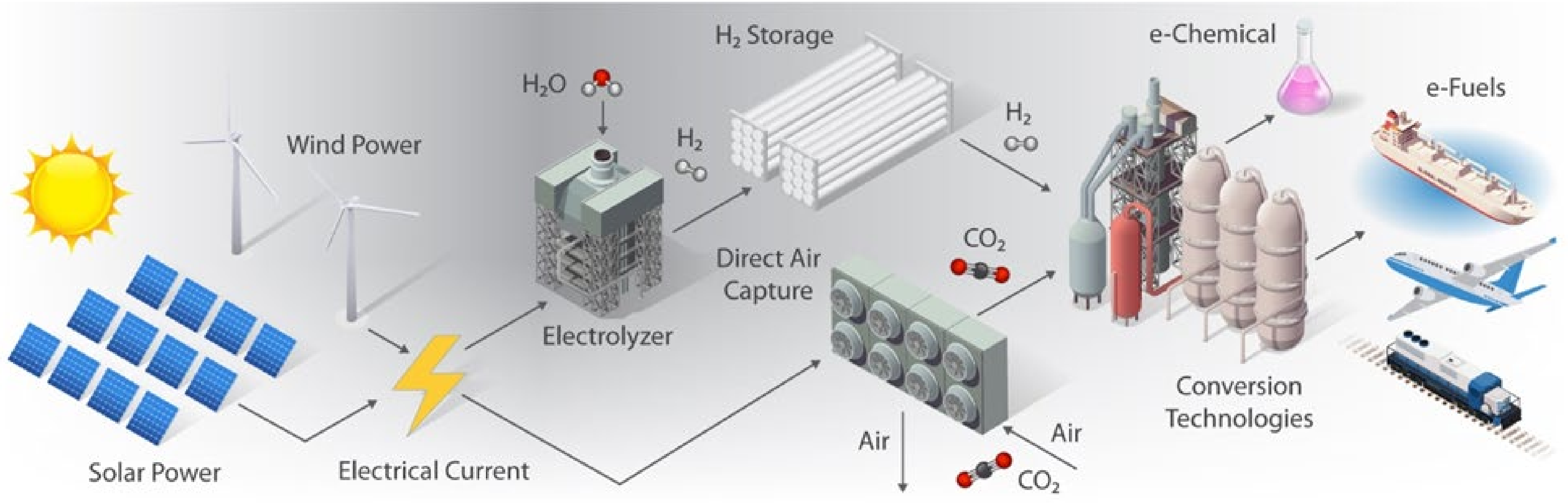
Ambitious EU-Wide Binding Share 2025-2050 (Source European Commission)

Refuel EU Aviation	2025	2030	2032	2035	2040	2045	2050
% SAF	2%	6%	6%	20%	34%	42%	70%
Aviation Biofuels and Recycled Carbon fuels (from waste)	2%	4.80%	4%	15%	24%	27%	35%
% synthetic SAF (e-SAF, PTL) from renewable power, nuclear allowed too		1.20%	2%	5%	10%	15%	35%

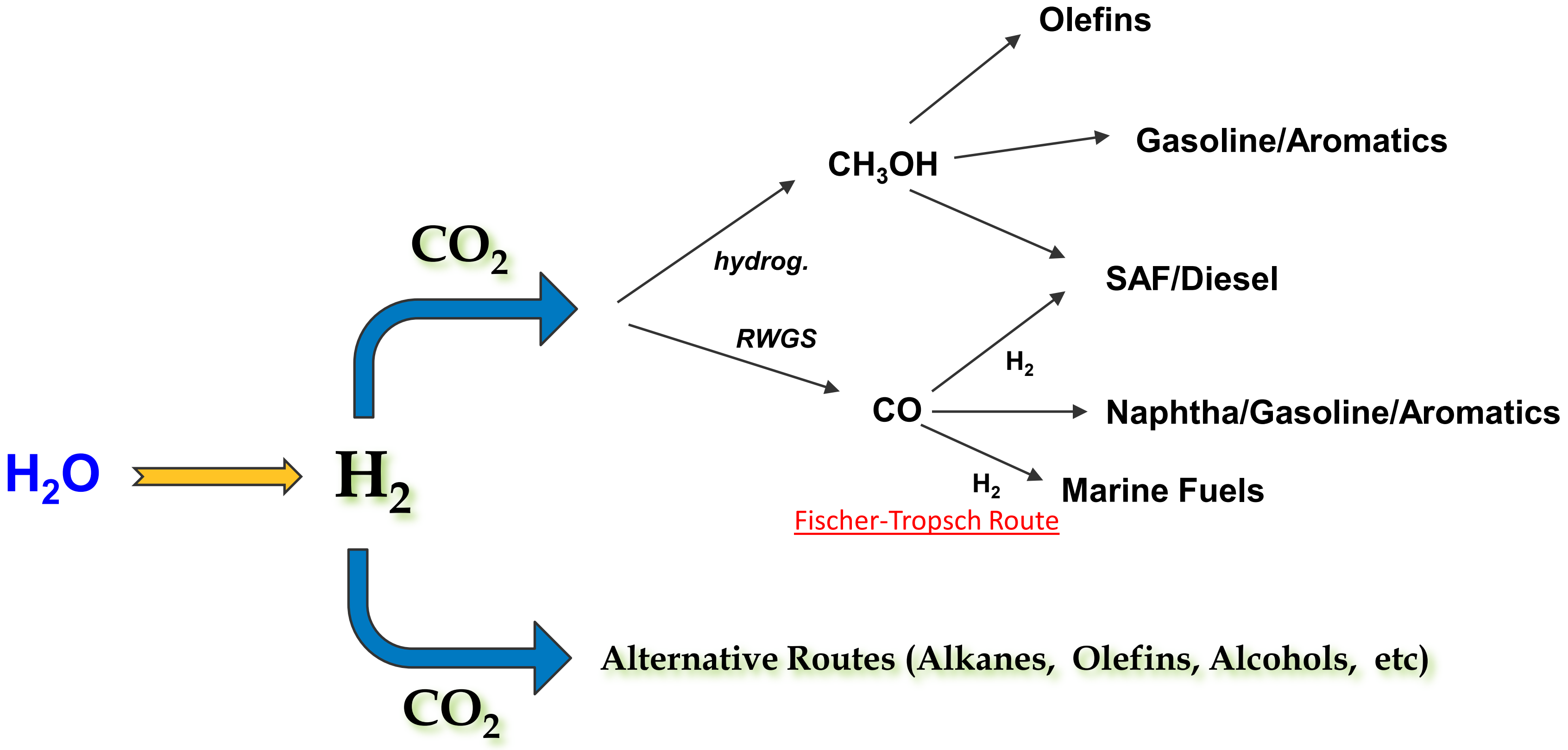
2030- 885 Million gallons SAF of which 174 million gallons is e-fuels
2035- 2.9 Billion gallons of SAF of which 721 million gallons is e-fuels

e-fuels and e-Chemicals
Generation of net zero/net negative e-Products

- E-fuels and e-chemicals require the integration of renewable electricity, electrolytic hydrogen generation, CO_2 capture, renewable heat generation, with existing and next generation conversion technologies.



E-Product Synthesis with H_2



cost, efficiency, energy, CO2 capture, catalysis, separations, scale, ….

-Many other chemistries are possible and will need to be developed

Payback Years for E-fuels

(Cost of Carbon $0/MT)

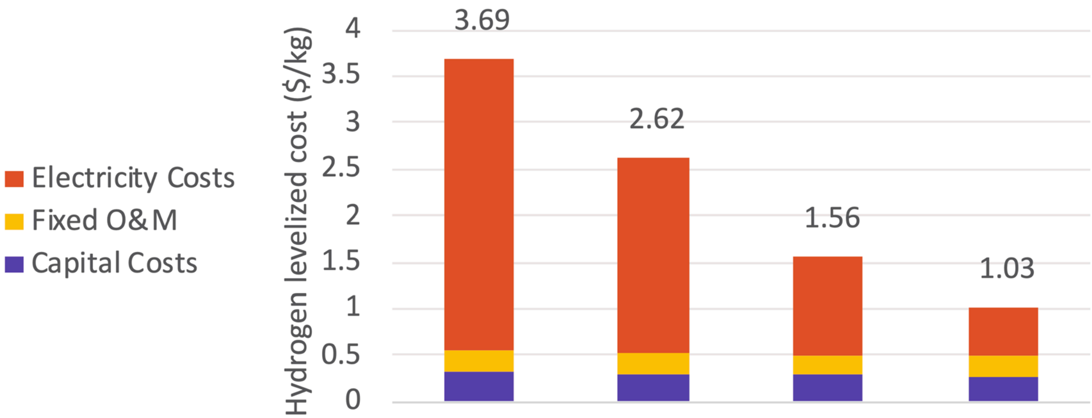
Capital Cost of $10 per gallon

Lowest Cost Alternative $5 per gallon

CO2 Cost $/MT	50	75	100	125	150	175	200	225	250	275	300	325	350	375	400	425	450	475	500
Hydrogen Cost $/kg																			
0.5	2.59	2.76	2.95	3.18	3.44	3.75	4.12	4.58	5.14	5.86	6.83	8.16	10.15	13.42	19.80	37.73	399.15	-46.52	-21.98
0.75	2.83	3.03	3.27	3.55	3.88	4.28	4.77	5.38	6.18	7.26	8.79	11.14	15.20	23.93	56.25	-160.70	-33.09	-18.44	-12.78
1	3.11	3.37	3.66	4.01	4.44	4.97	5.65	6.53	7.75	9.52	12.34	17.53	30.25	110.48	-66.89	-25.67	-15.88	-11.50	-9.01
1.25	3.47	3.78	4.16	4.62	5.20	5.94	6.93	8.31	10.38	13.83	20.69	41.11	3092.83	-42.23	-20.97	-13.95	-10.45	-8.36	-6.96
1.5	3.91	4.32	4.82	5.45	6.27	7.37	8.96	11.42	15.72	25.25	64.11	-118.98	-30.86	-17.73	-12.44	-9.58	-7.79	-6.56	-5.67
1.75	4.49	5.03	5.72	6.63	7.88	9.72	12.68	18.22	32.39	145.58	-58.37	-24.31	-15.35	-11.22	-8.84	-7.29	-6.21	-5.40	-4.78
2	5.26	6.02	7.03	8.46	10.62	14.26	21.67	45.16	-538.02	-38.67	-20.06	-13.54	-10.22	-8.21	-6.86	-5.89	-5.16	-4.59	-4.13
2.25	6.35	7.49	9.14	11.71	16.28	26.73	74.54	-94.46	-28.91	-17.07	-12.11	-9.38	-7.66	-6.47	-5.60	-4.94	-4.41	-3.99	-3.64
2.5	8.02	9.93	13.04	18.98	34.86	213.34	-51.77	-23.09	-14.85	-10.95	-8.67	-7.18	-6.12	-5.34	-4.73	-4.25	-3.86	-3.53	-3.25
2.75	10.87	14.71	22.75	50.10	-247.48	-35.66	-19.21	-13.15	-10.00	-8.06	-6.75	-5.81	-5.10	-4.54	-4.10	-3.73	-3.42	-3.16	-2.94
3	16.88	28.38	89.02	-78.32	-27.20	-16.45	-11.80	-9.19	-7.53	-6.38	-5.53	-4.88	-4.37	-3.96	-3.61	-3.32	-3.08	-2.87	-2.68
3.25	37.73	399.15	-46.52	-21.98	-14.39	-10.69	-8.51	-7.07	-6.04	-5.28	-4.68	-4.21	-3.82	-3.50	-3.23	-3.00	-2.80	-2.62	-2.47
3.5	-160.70	-33.09	-18.44	-12.78	-9.78	-7.92	-6.66	-5.74	-5.04	-4.50	-4.06	-3.70	-3.40	-3.14	-2.92	-2.73	-2.56	-2.41	-2.28
3.75	-25.67	-15.88	-11.50	-9.01	-7.41	-6.29	-5.47	-4.83	-4.33	-3.92	-3.58	-3.30	-3.06	-2.85	-2.67	-2.51	-2.36	-2.24	-2.12
4	-13.95	-10.45	-8.36	-6.96	-5.96	-5.22	-4.64	-4.17	-3.79	-3.48	-3.21	-2.98	-2.78	-2.61	-2.45	-2.32	-2.19	-2.08	-1.99

For electrolysis at scale, electricity prices are the largest component of the hydrogen production cost

Historically, electricity prices have been fixed in technoeconomic assessments (TEAs)



Electricity price	$0.06/kWh	$0.04/kWh	$0.02/kWh	$0.01/kWh
Capital cost	$400/kW	$400/kW	$400/kW	$400/kW
Capacity factor	97%	97%	97%	97%

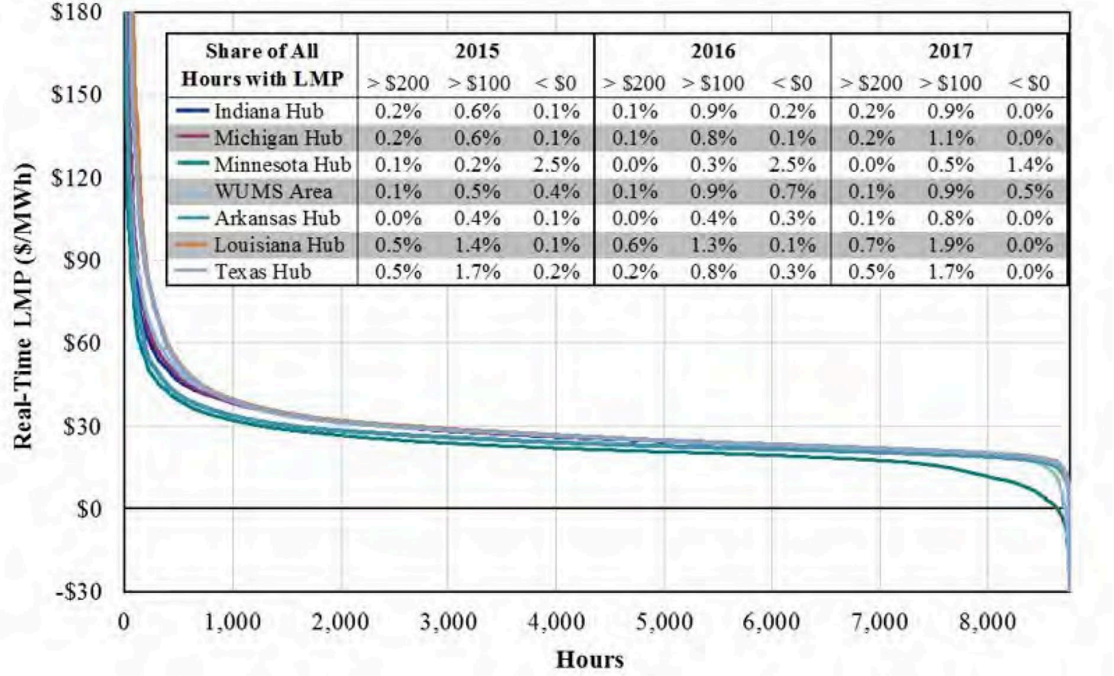
H2A Future Central case. 51.3 kWh/kg system efficiency. Capital costs are total system purchase cost.

Badgett, A., Ruth, M. and Pivovar, B. (2022) ‘Chapter 10 - Economic considerations for hydrogen production with a focus on polymer electrolyte membrane electrolysis’, in Smolinka, T. and Garche, J. (eds) *Electrochemical Power Sources: Fundamentals, Systems, and Applications*. Elsevier, pp. 327–364.

Electrolysis Economics are Driven by Electricity Prices

Electricity Prices Vary Across the Year

Figure A2: Real-Time Energy Price-Duration Curve
2017



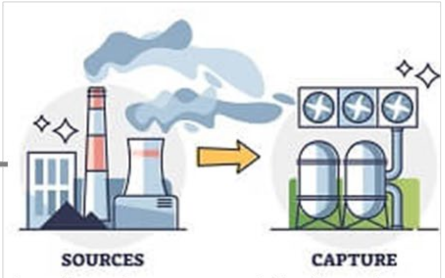
Share of All Hours with LMP	2015			2016			2017		
	> $200	> $100	< $0	> $200	> $100	< $0	> $200	> $100	< $0
Indiana Hub	0.2%	0.6%	0.1%	0.1%	0.9%	0.2%	0.2%	0.9%	0.0%
Michigan Hub	0.2%	0.6%	0.1%	0.1%	0.8%	0.1%	0.2%	1.1%	0.0%
Minnesota Hub	0.1%	0.2%	2.5%	0.0%	0.3%	2.5%	0.0%	0.5%	1.4%
WUMS Area	0.1%	0.5%	0.4%	0.1%	0.9%	0.7%	0.1%	0.9%	0.5%
Arkansas Hub	0.0%	0.4%	0.1%	0.0%	0.4%	0.3%	0.1%	0.8%	0.0%
Louisiana Hub	0.5%	1.4%	0.1%	0.6%	1.3%	0.1%	0.7%	1.9%	0.0%
Texas Hub	0.5%	1.7%	0.2%	0.2%	0.8%	0.3%	0.5%	1.7%	0.0%

Source: Potomac Economics 2017 State of the Market Report for the MISO Electricity Market – Analytic Appendix (June 2018)

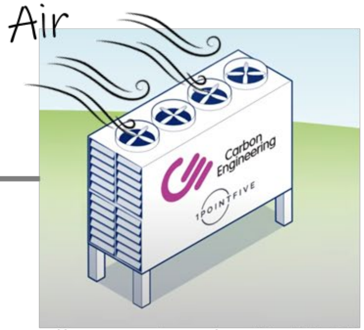
- Hours with energy at very low and very high prices are increasing
- Other revenue streams (e.g., capacity, services) are becoming more critical
- Wind and solar power purchase agreements (PPAs) are key opportunities

Three Types of CO_2 Capture

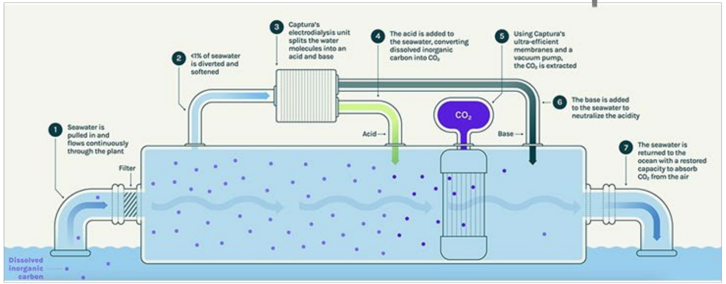
1. Point-source CO_2 capture
2. Direct air capture
3. Direct ocean capture



https://www.theecoexperts.co.uk/blog/does-carbon-capture-work

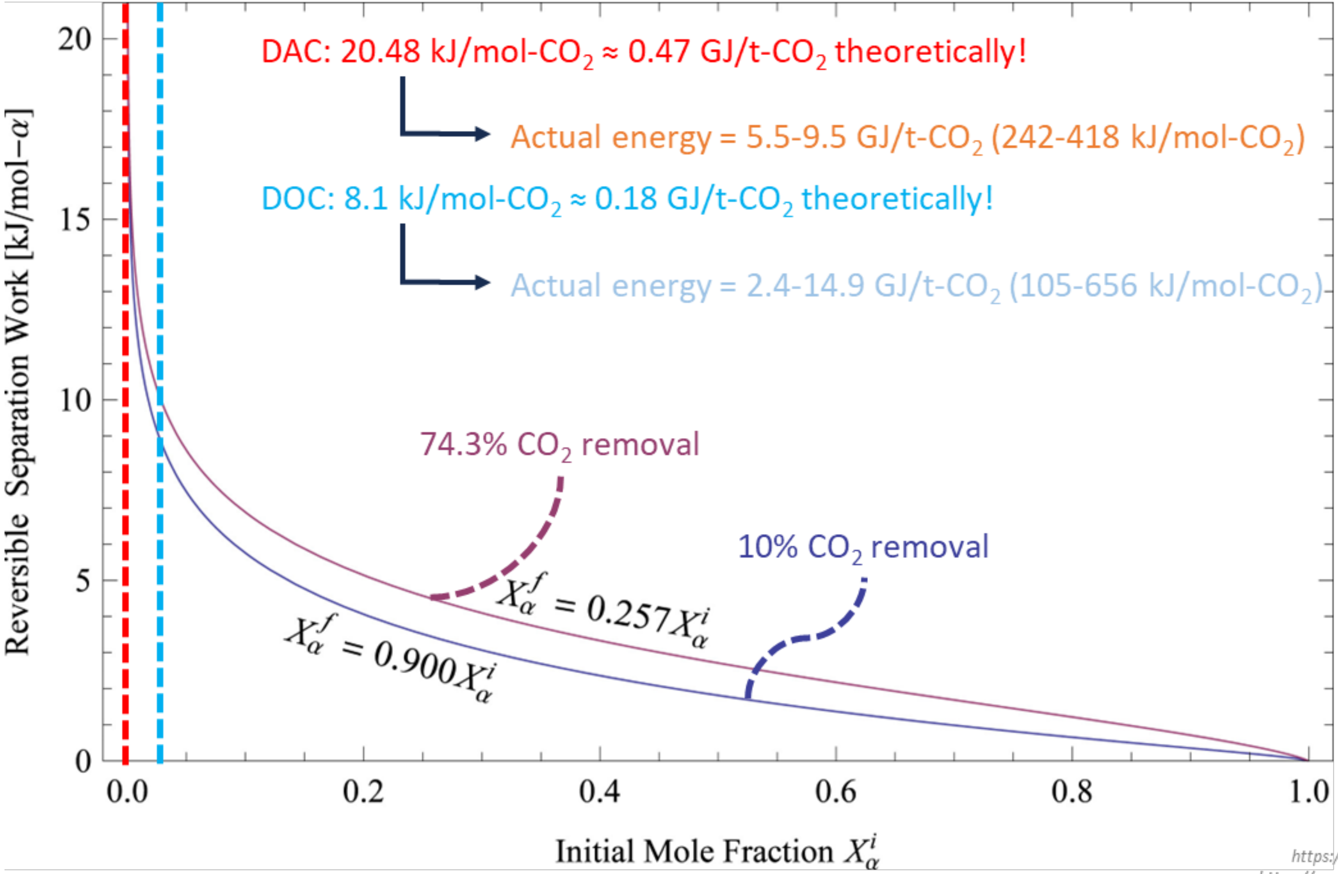


https://www.youtube.com/watch?v=zYhIq-TlDLo



https://capturacorp.com/technology/

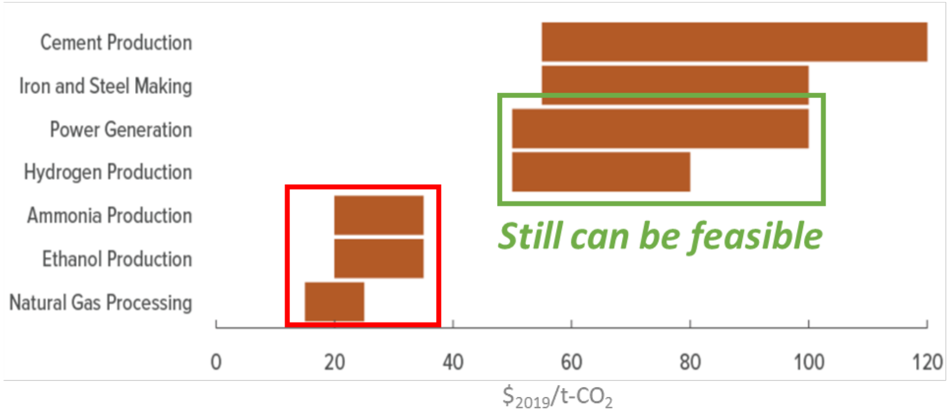
Separation of CO2 from Air/Ocean

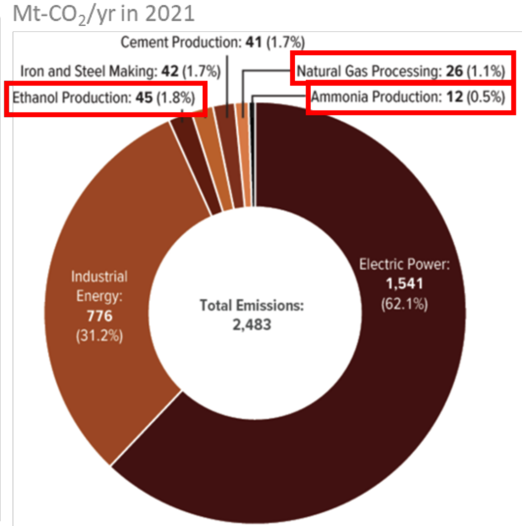


https://doi.org/10.1016/j.xcrp.2022.100791
https://www.iea.org/reports/direct-air-capture-2022

Point-Source CO2 Capture Costs *(U.S. Data)*

- The cheapest point-source CO_2 capture is for:
  - Ammonia production, ethanol production, and NG processing ← due to high [CO_2] = *easier separation*
- Highest CO_2 emissions come from:
  - Industrial energy and electric power (≈ 93.3%!)





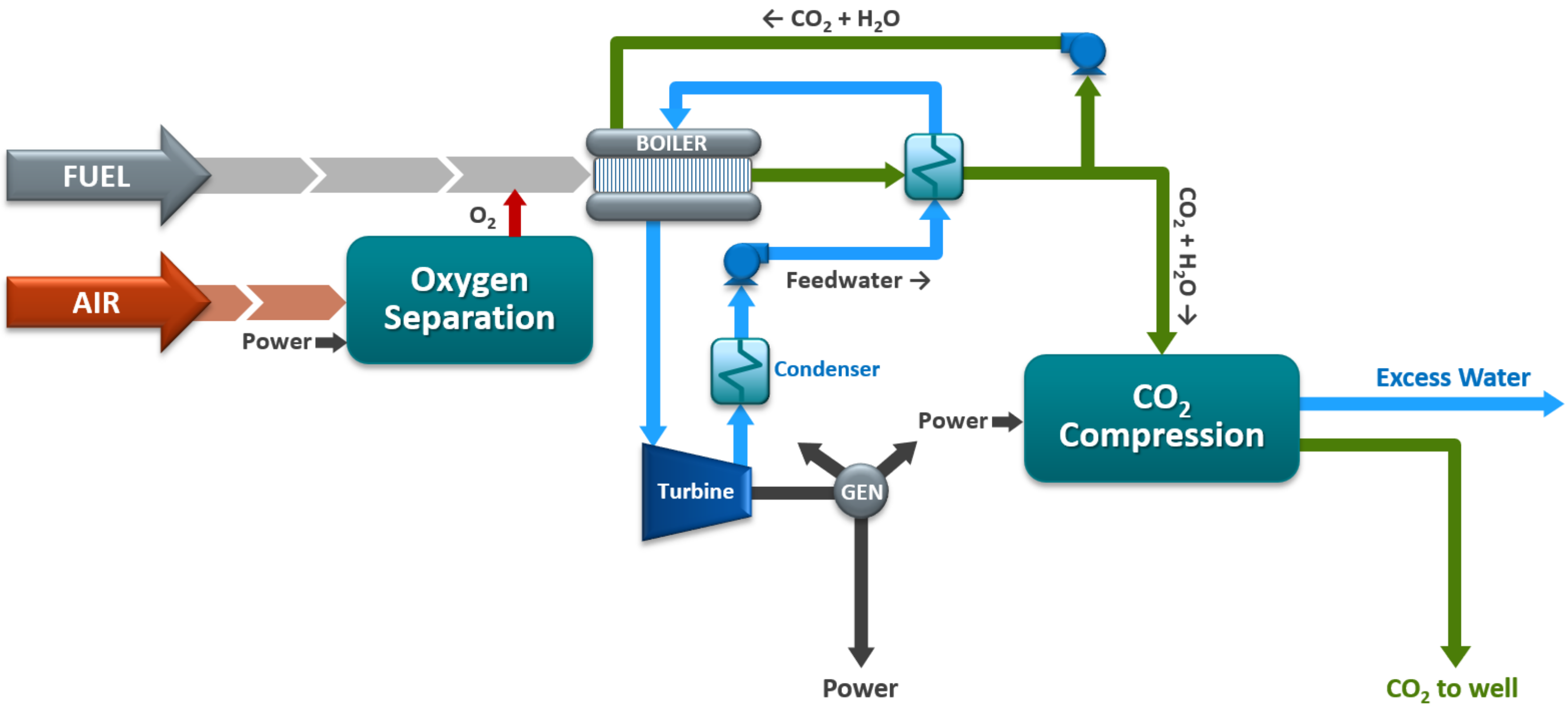
https://www.cbo.gov/publication/59832#_idTextAnchor021

Biogenic CO_2 Sources in USA

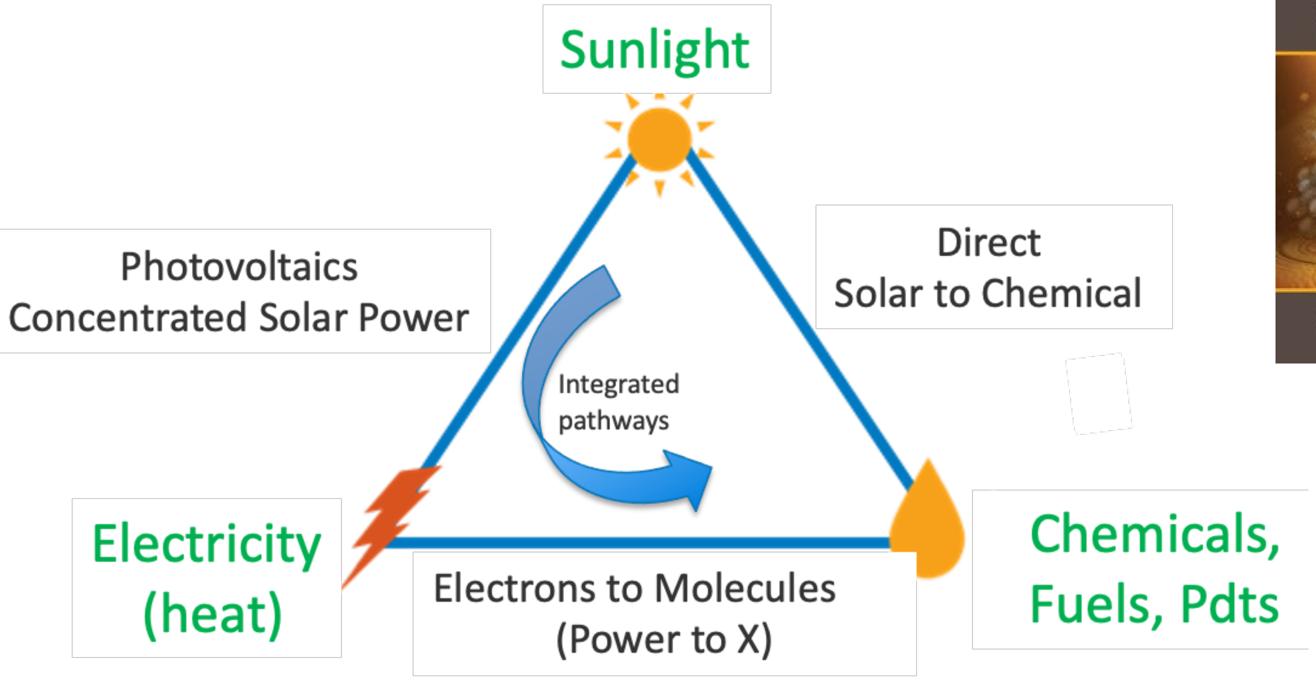
Biogenic CO_2 Source	Tons of CO_2	Gallons of e-fuels (100 gallons per ton)	
CO_2 from Corn Ethanol	41,369,900	4,136,990,000	https://www.sciencedirect.com/science/article/abs/pii/S0360128517300114
Black Liquor Combustion	73,500,000	7,350,000,000	https://www.epa.gov/system/files/documents/2023-02/US-GHG-Inventory-2023-Main-Text.pdf#page122
Woody Biomass Combustion	146,500,000	14,650,000,000	https://www.epa.gov/system/files/documents/2023-02/US-GHG-Inventory-2023-Main-Text.pdf#page122
Landfills and Animal Manure	3,008,556	300,855,600	https://www.sciencedirect.com/science/article/abs/pii/S0360128517300114

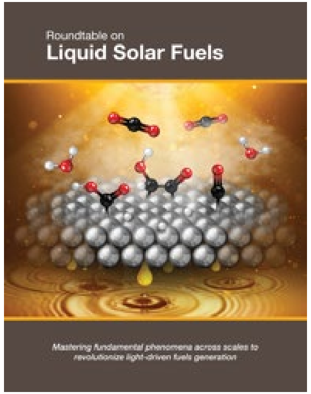
Total Gallons 26,437,845,600

BECCS with Oxy-Combustion



Solar Fuels—Electrolysis: Direct conversion of sunlight to chemicals/fuels



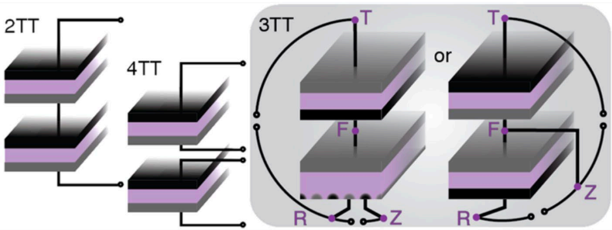


https://science.osti.gov/bes/Community-Resources/Reports

http://mission-innovation.net/wp-content/uploads/2021/03/Converting-Sunlight-into-Solar-Fuels-and-Chemicals-MI-Challenge-5-roadmap-Feb-2021-final.pdf

https://www.liquidsunlightalliance.org
https://solarhub.unc.edu/

Selectivity via co-design in PEC CO_2RR

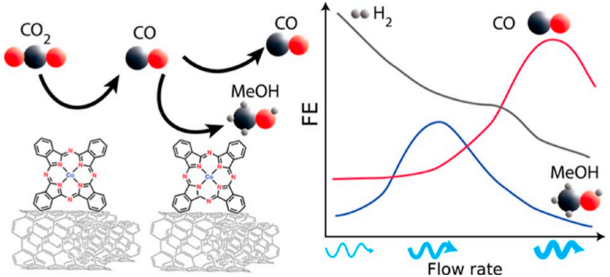


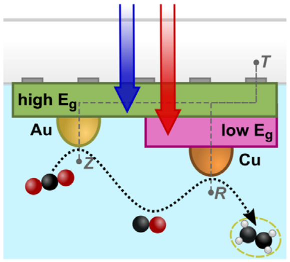
Three-terminal tandems enable multiple potentials

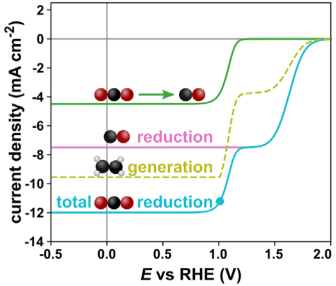
Warren, et al. *ACS Energy Letters*, **2020**, *4*, 1233-1242.

Single catalyst can drive different CO_2RR steps at different potentials

Kong, et al. *ACS Appl. Energy Mater.*, **2024**, *7*, 3091-3098.

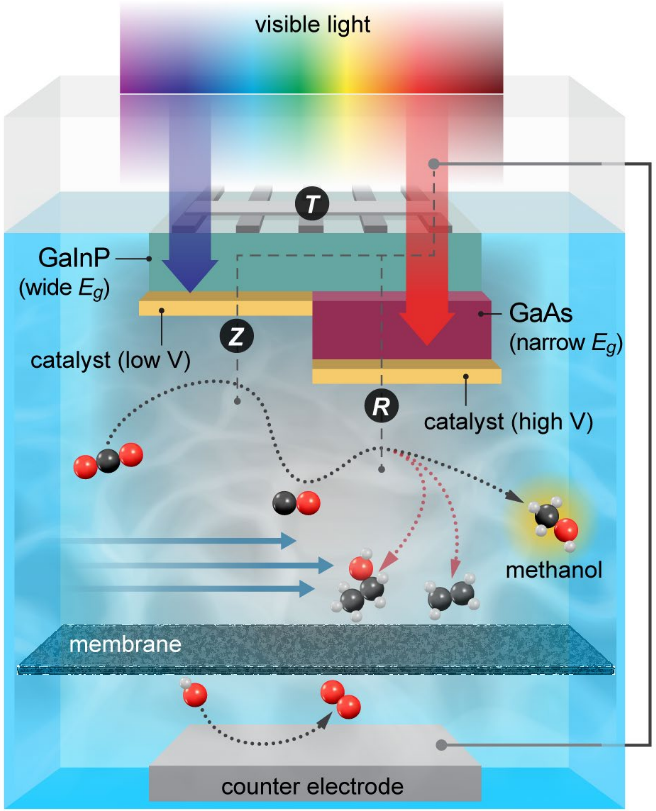






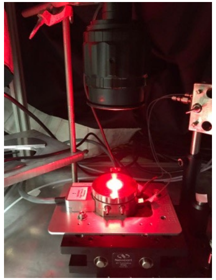
Modelling indicates operational benefits from integrated photocathode

Kong, et al. *Sustain. Energy Fuels*, **2021**, *5*, 6361-6371.



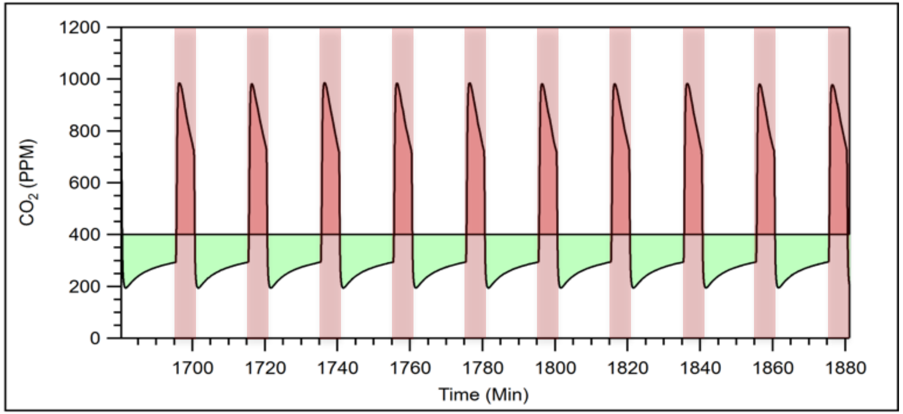
Energy Fuels **2021**, *5*, 6361–6371.
US Patent 11,961,927 B2, Apr. 16, 2024
Greenaway et al. Energy and Fuels **39,** 3703 (2025)

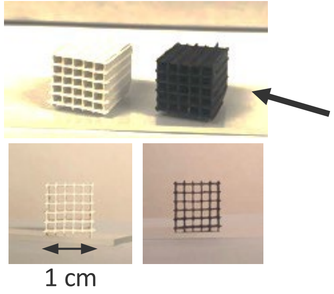
Photo(thermal)-Swing DAC



Aminopolymer-Based Photo-DAC

- Baseline system prior to photo-RCC integration
- Utilizes inexpensive, earth-abundant components (TiO_2 air contactor, TiN absorber)
- Exhibits rapid CO_2 desorption kinetics
- Demonstrated ~90% capacity retention over **2000 cycles**





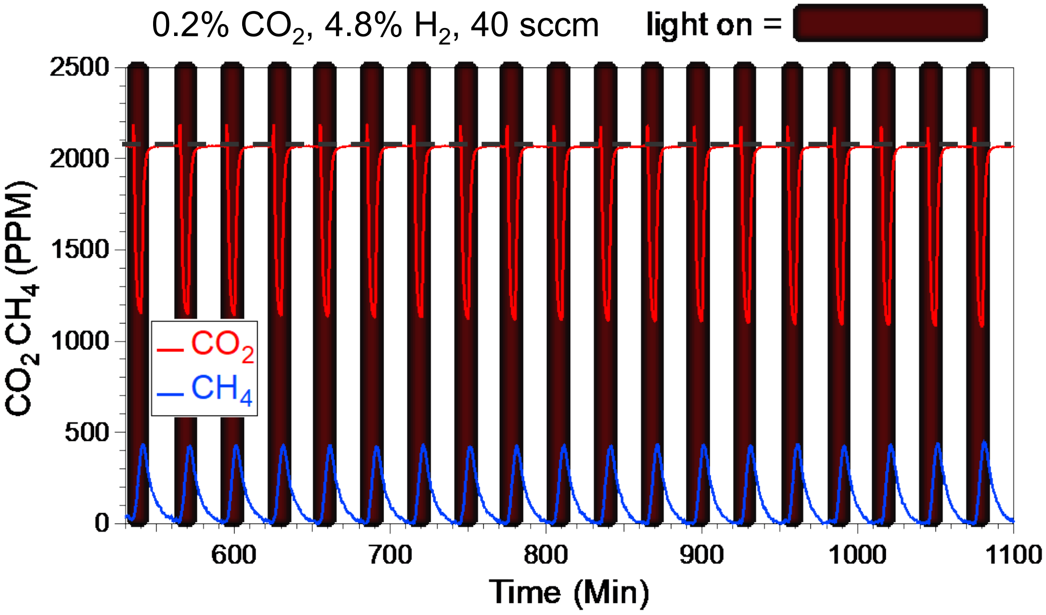
Visible light absorbing air contactor w/ plasmonic Titanium Nitride NPs

Noemi Leick*, et. al, "Photo-swing CO_2 capture using aminopolymers as sorbents and TiN light absorber", *ACS Sustain. Chem. Eng.*, **2025**, submitted.
DOI: 10.26434/chemrxiv-2024-b5wjj

Photomethanation of CO_2

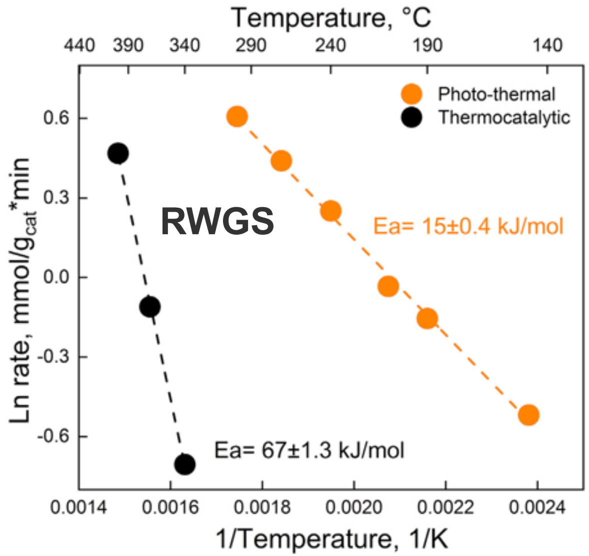
ACS Appl. Energy Mater. 2025, 8, 18, 13179-13184

Photomethanation achieved in a DAC system ***without degrading the amine***!



Light on 5 min, Dark 25 min

Other photochemistries



https://doi.org/10.1016/j.isci.2022.104107

Thank you

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Randy D. Cortright, Ph.D.
Strategic Lead for Electrons to Molecules
Senior Research Advisor

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