



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

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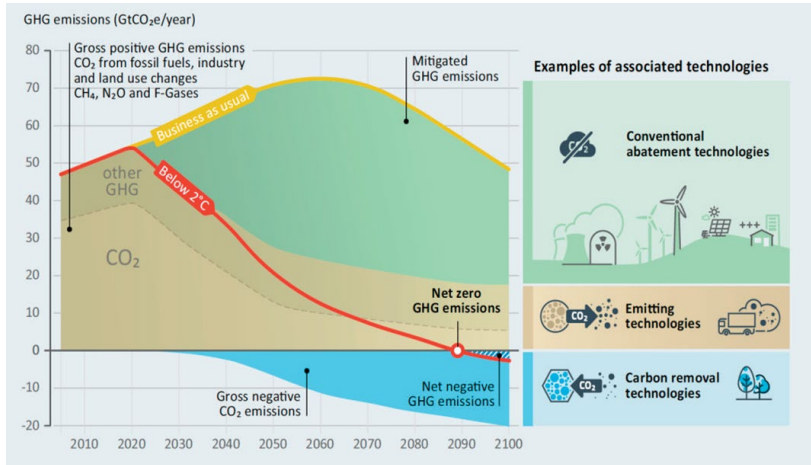
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Bill Tumas, Associate Lab Director

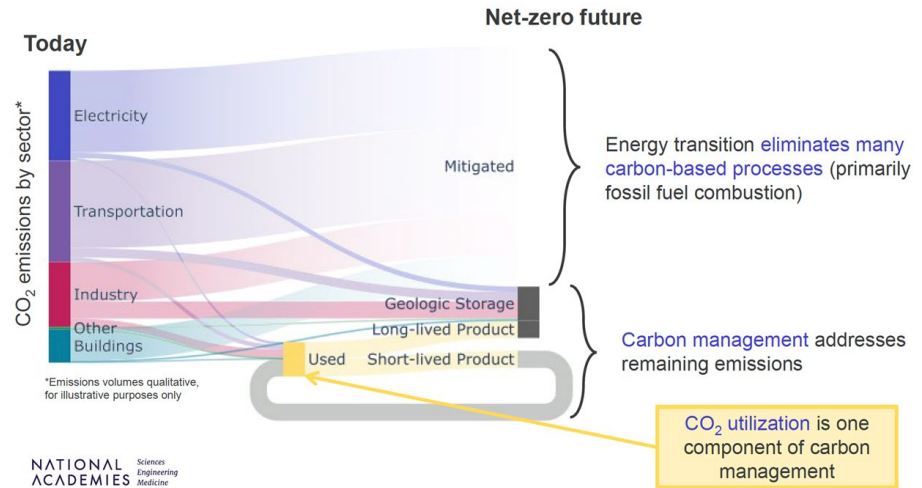
September 30, 2025

Strategy for CO₂ Emissions

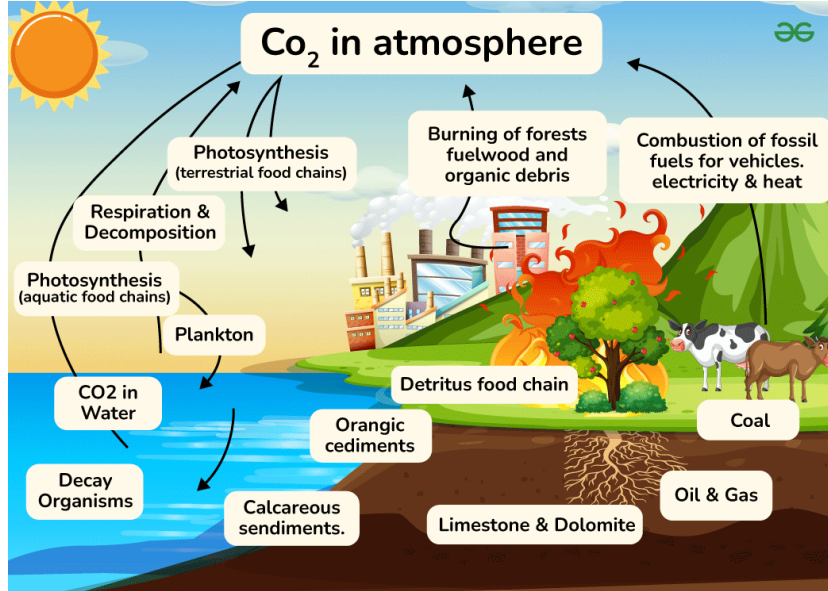
- Eliminate CO₂ emissions through energy transition (electrification)
- Utilize Carbon Management Technologies to address remaining emissions
- Carbon Dioxide Removal (CDR) for rolling back atmospheric CO₂ Concentrations



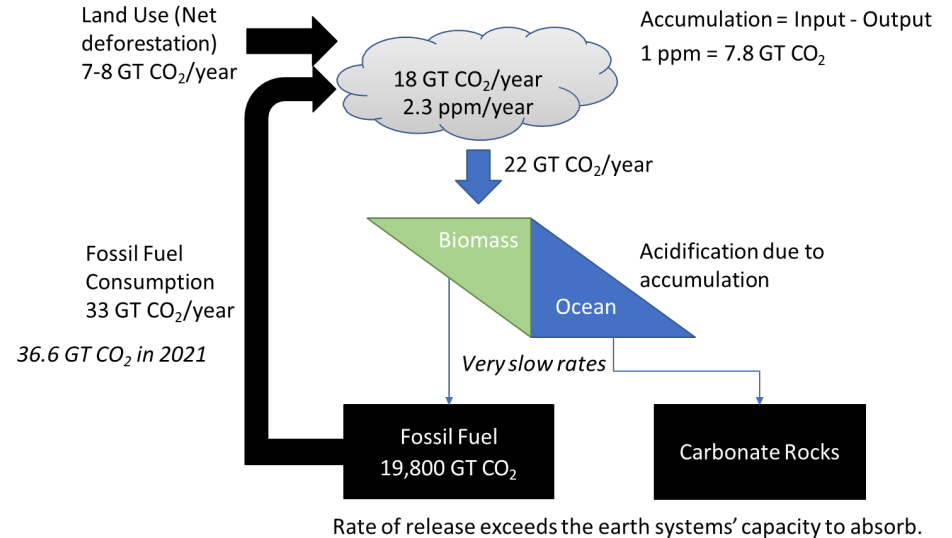
Targeting a Net-Zero CO₂ Emissions System



Carbon Cycle

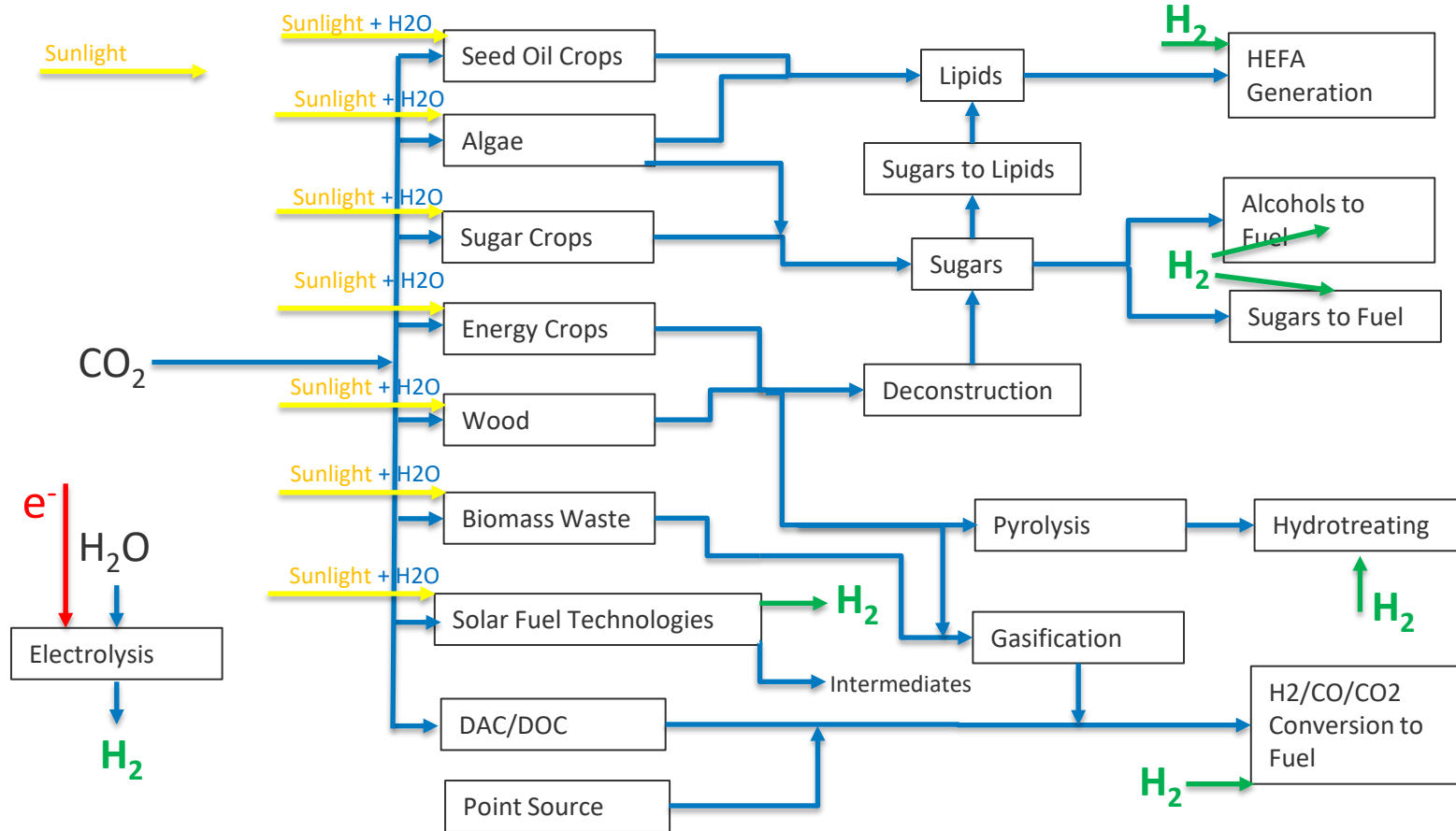


The Global Carbon Cycle



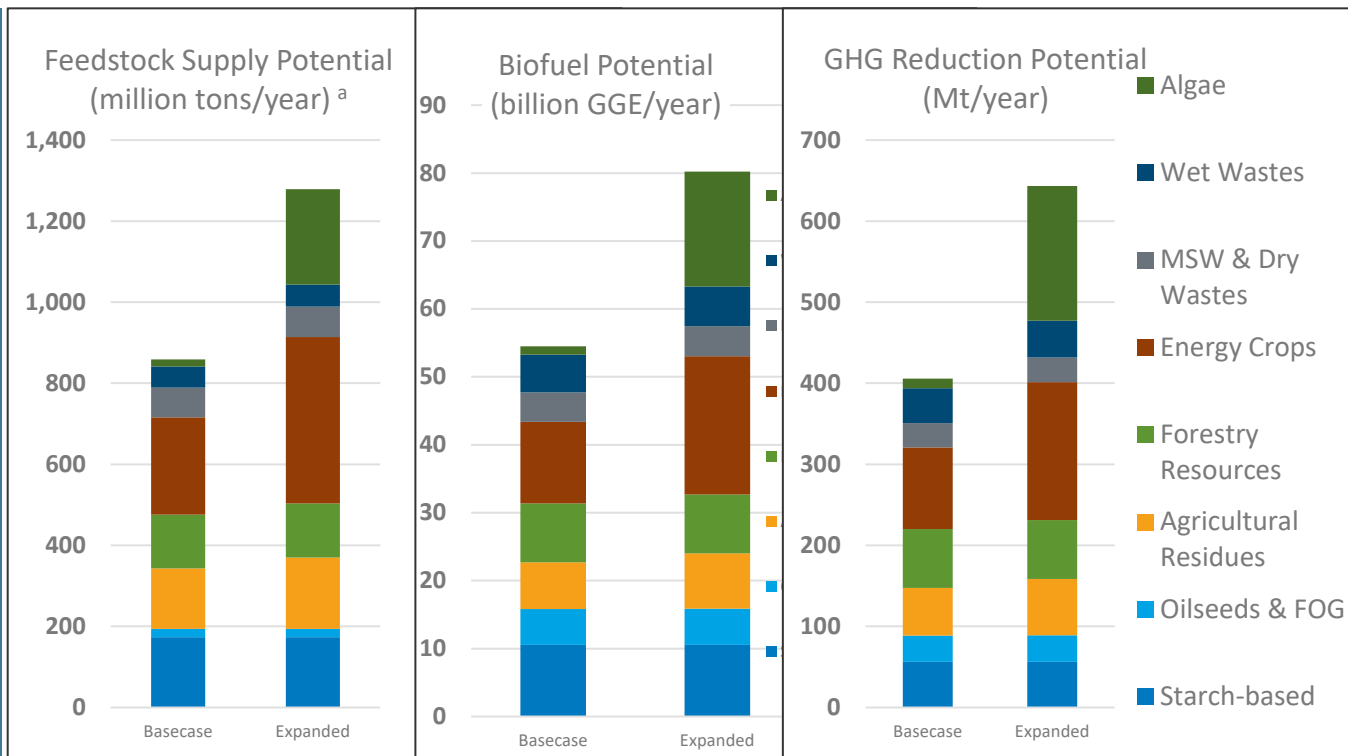
MJ Realf, P Eisenberger, Flawed analysis of the possibility of air capture. Proc Natl Acad Sci USA 109, E1589 (2012)

Sustainable Fuel Roadmap



US Biomass Feedstock Supply and Biofuel Potential

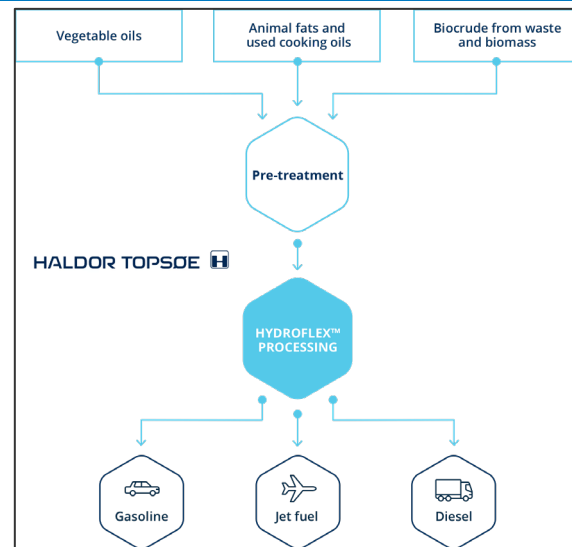
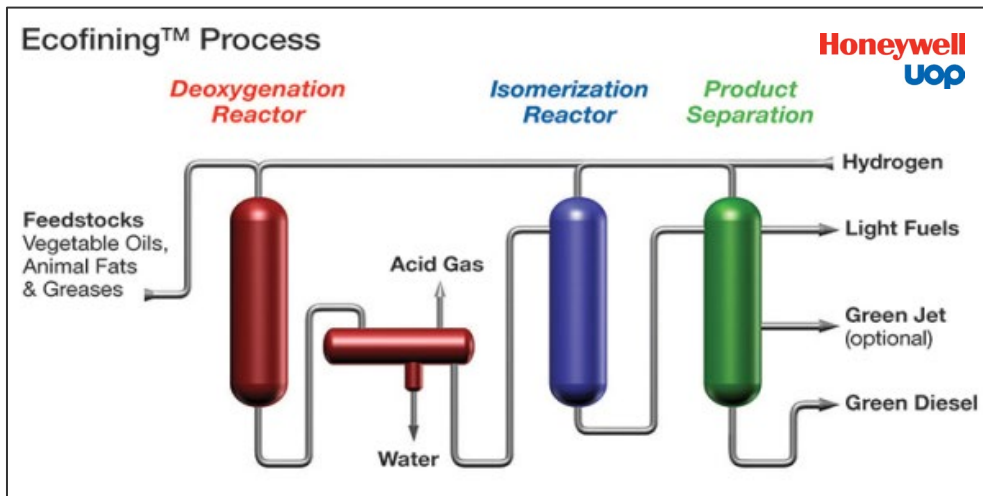
- Carbon feedstocks
 - 858 to 1,279 million tons/yr.
- Fuel production
 - 55 to 80 billion GGE/yr.
 - US Fuel Consumption is 220 billion gallons
- Total GHG emissions saving
 - 406 to 644 million tons/yr.



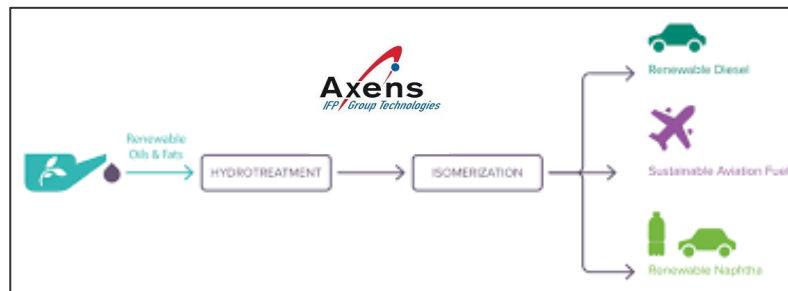
^a Dry and wet waste feedstocks are reported on a dry basis. Algae is reported on an AFDW dry basis. Starch-based, oilseed, and waste FOG are reported on an as-received basis.

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

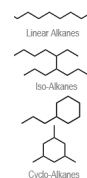
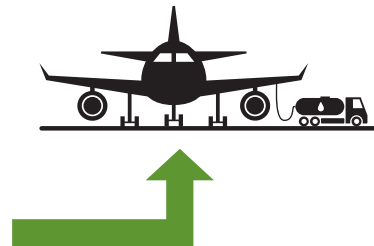
Fats, Oils, Greases
FT Waxes & Oils
Alcohols
Bio-Oils/Biocrudes
Ketones
Sugars
Algae Oils
Lignins

Pretreatment of Feeds to Meet Critical Material Attributes (CMA)



Petroleum Refinery

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

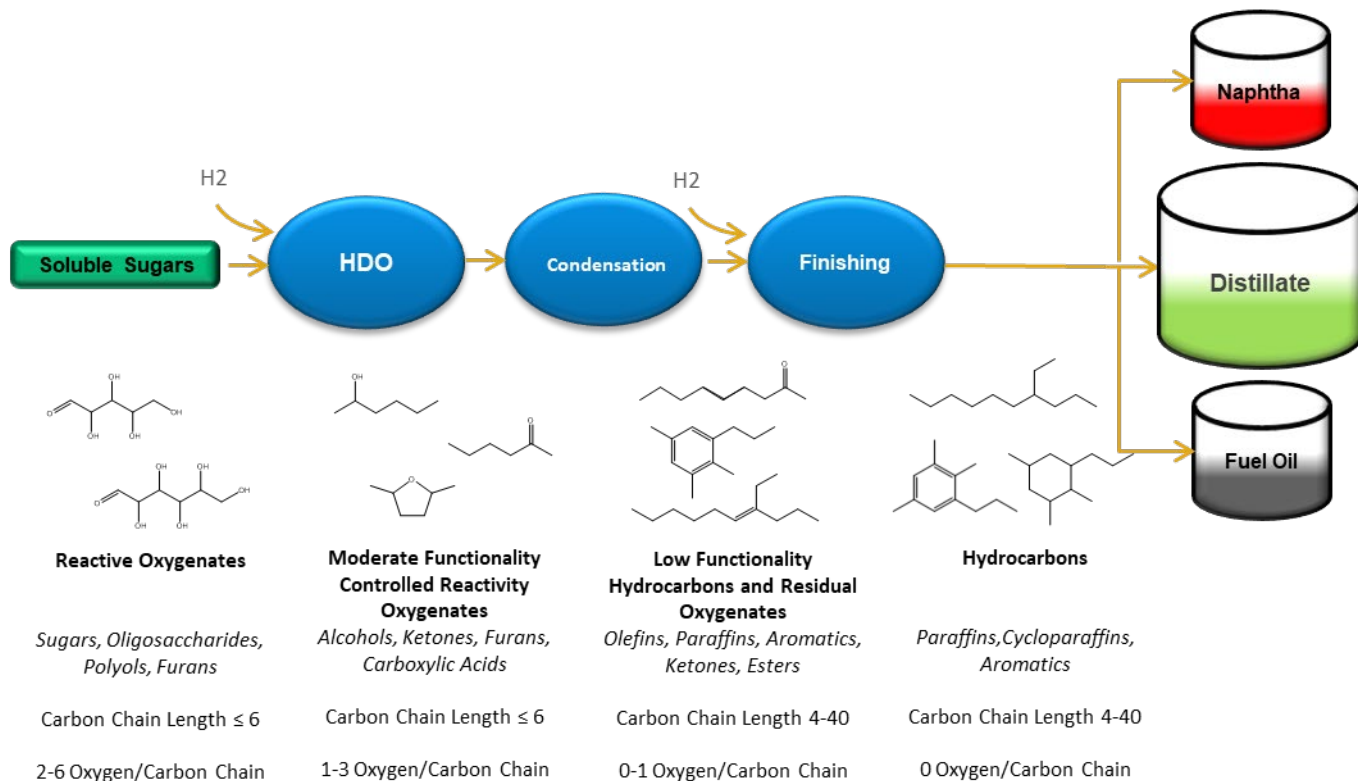


- Fuel QA/QC
- Fuel delivery
- Fuel branding

Critical Material Attributes (CMA)

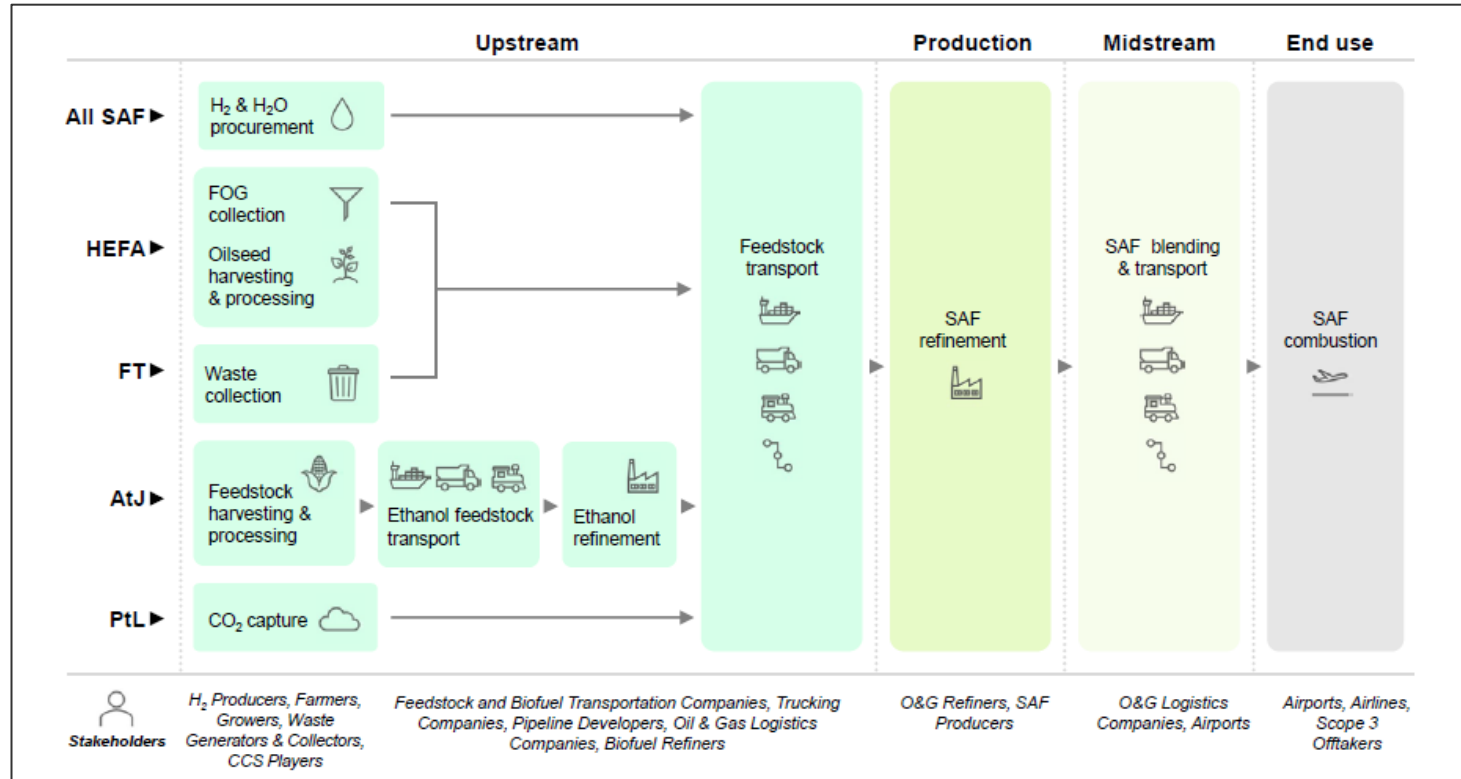
- These are physical and chemical properties of pretreated renewable streams which can be processed by refineries with no or minor modifications

Virent's BioForming[®] Distillate Process Chemistry



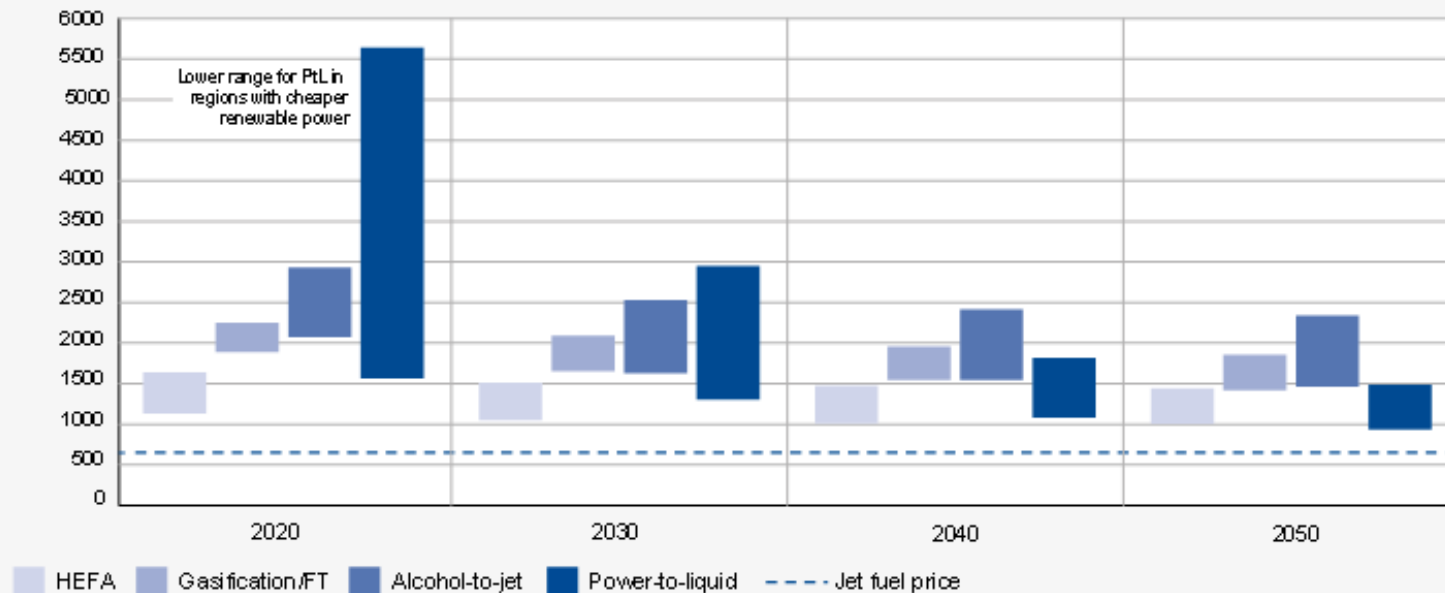
US Patents 9,944,869, 9,593,054, 9,228,134, 9,217,114, 9,206,366, 8,933,281, 8,455,705, 8,367,882, 8,362,307, 8,053,015, 8,017,818, 7,977,517

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



Transition of Sources of SAF

Global SAF production cost for selected feedstocks *Indicative*



Source: Expert interviews

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%

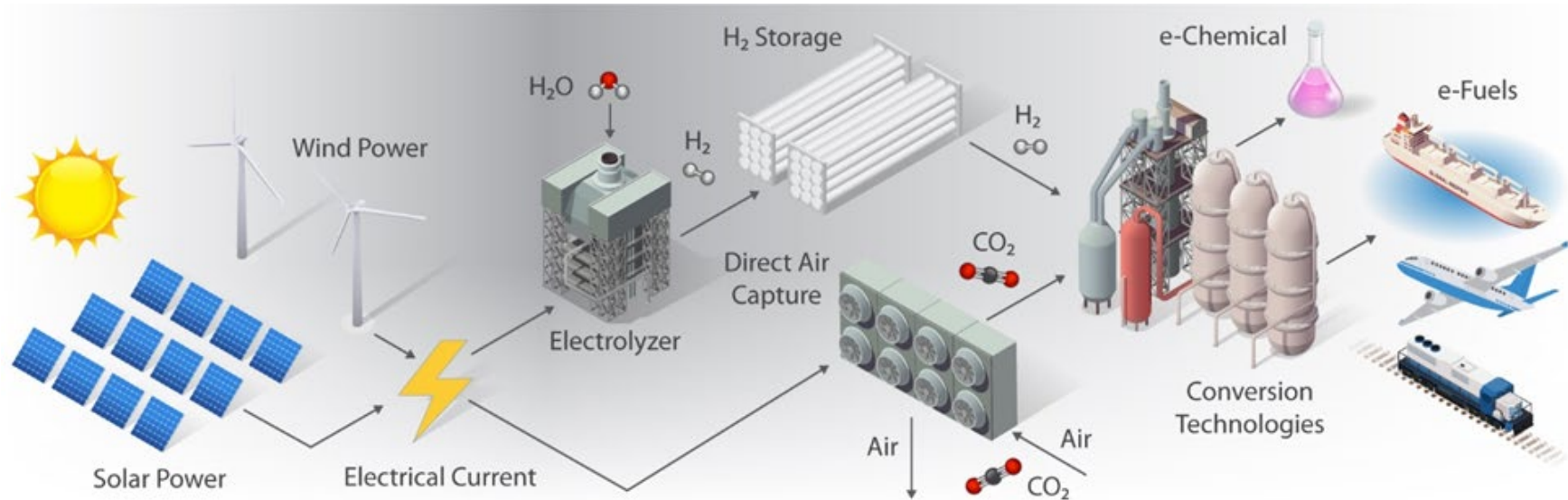
2030- 885 Million gallons SAF of which 174 million gallons is e-fuels

2035- 2.9 Billion gallons of SAF of which 721 million gallons is e-fuels

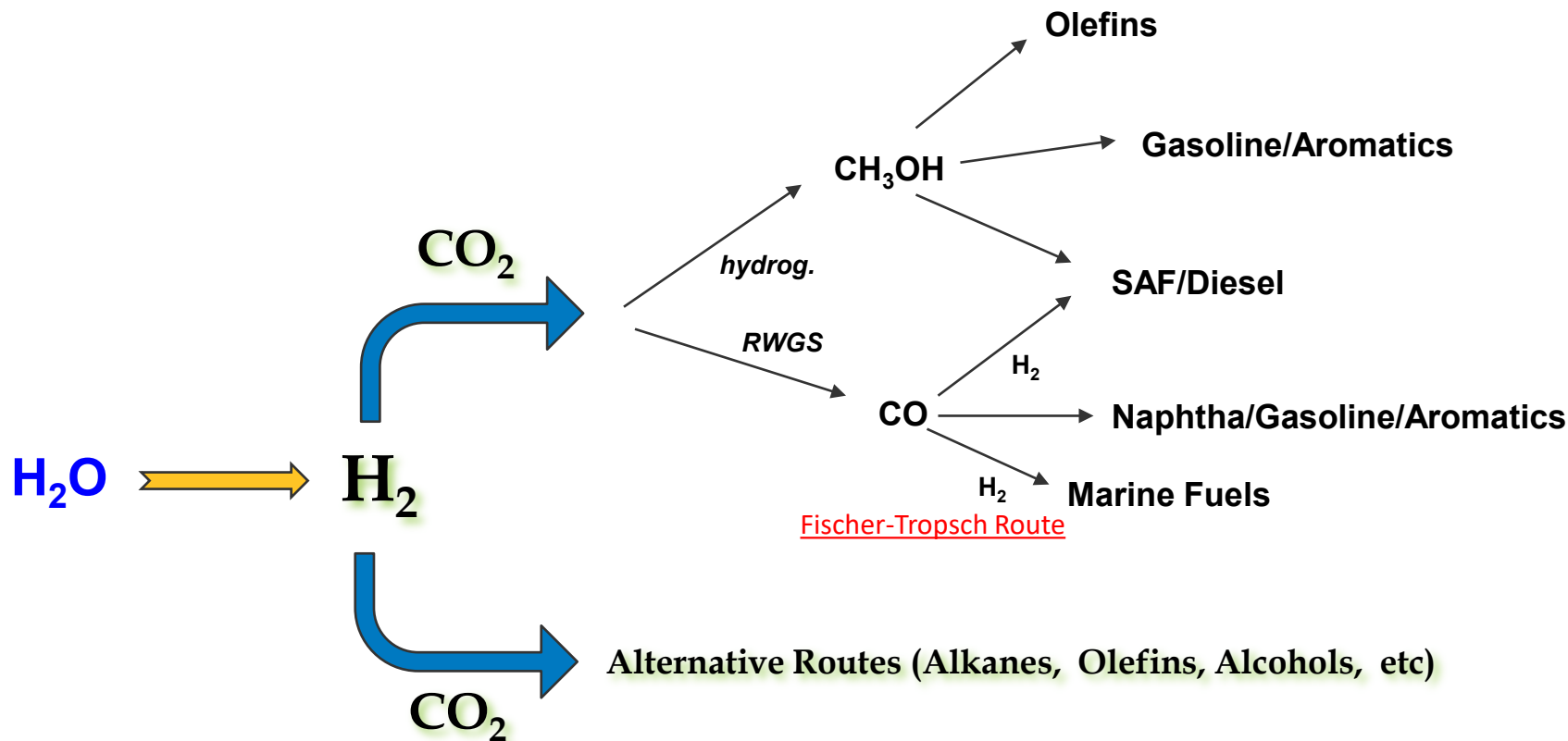
e-fuels and e-Chemicals

Generation of net zero/net negative e-Products

- E-fuels and e-chemicals require the integration of renewable electricity, electrolytic hydrogen generation, CO₂ capture, renewable heat generation, with existing and next generation conversion technologies.



E-Product Synthesis with H₂



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)

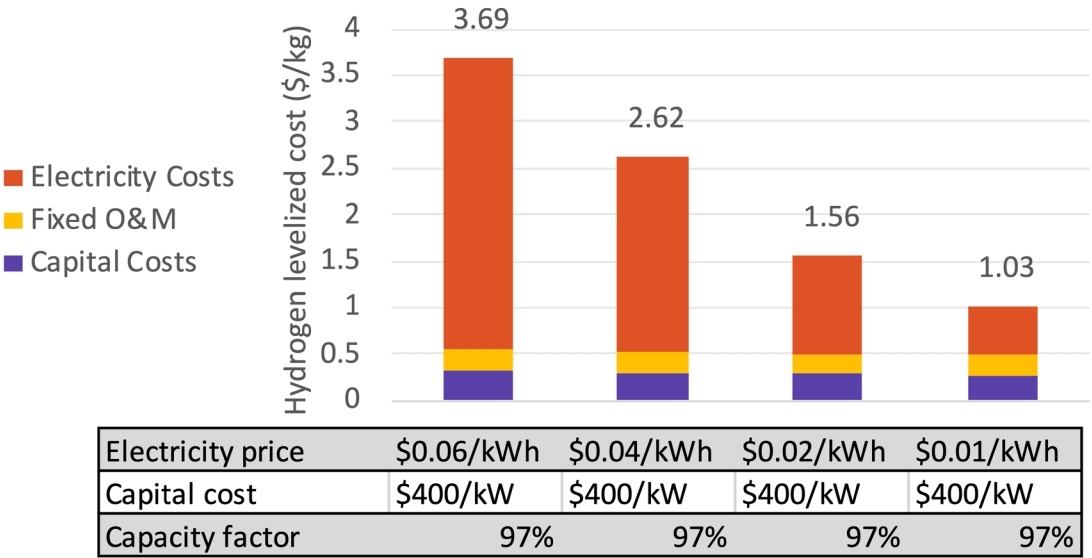
Capital Cost of \$10 per gallon

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)



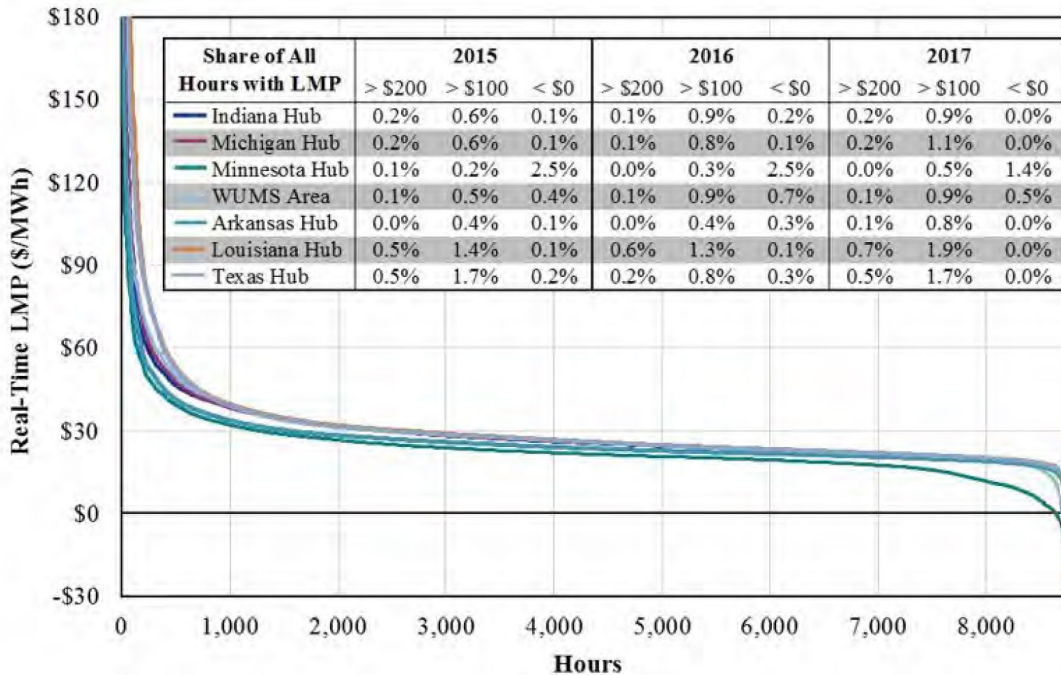
H2A Future Central case. 51.3 kWh/kg system efficiency. Capital costs are total system purchase cost.

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

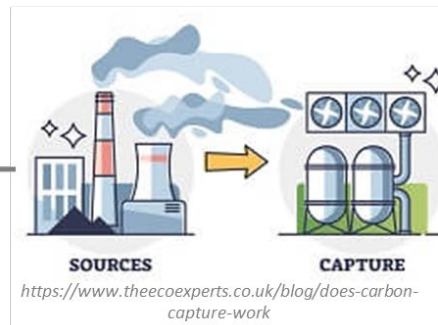


- Hours with energy at very low and very high prices are increasing
- Other revenue streams (e.g., capacity, services) are becoming more critical
- Wind and solar power purchase agreements (PPAs) are key opportunities

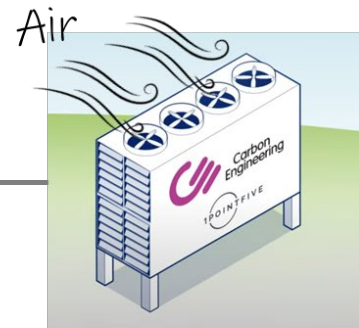
Source: Potomac Economics 2017 State of the Market Report for the MISO Electricity Market – Analytic Appendix (June 2018)

Three Types of CO₂ Capture

1. Point-source CO₂ capture

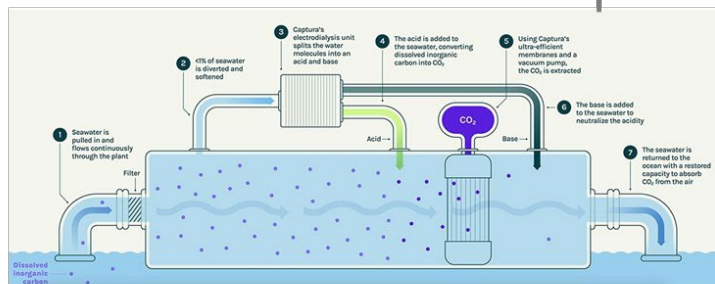


2. Direct air capture



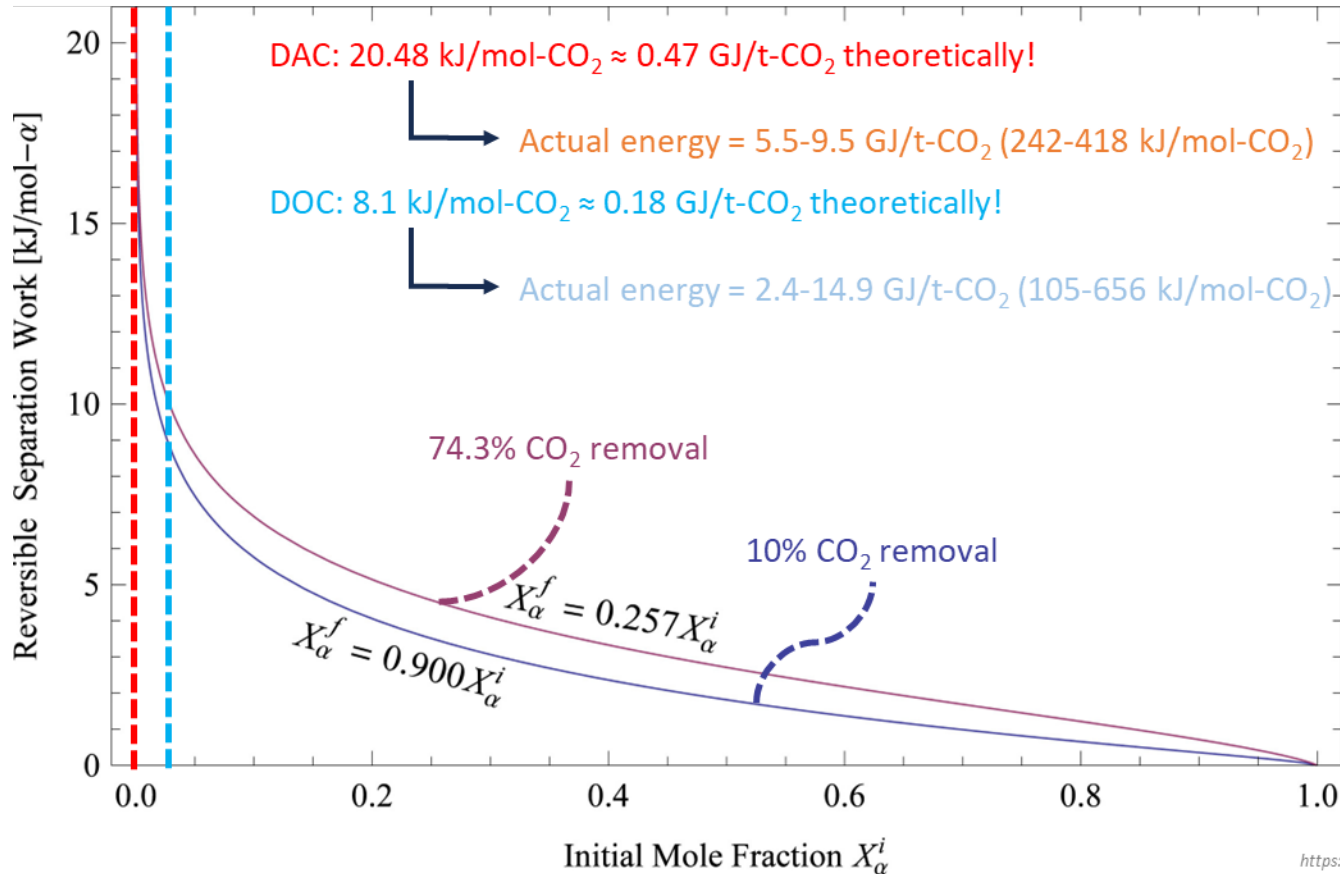
<https://www.youtube.com/watch?v=zYhlq-TIDLo>

3. Direct ocean capture



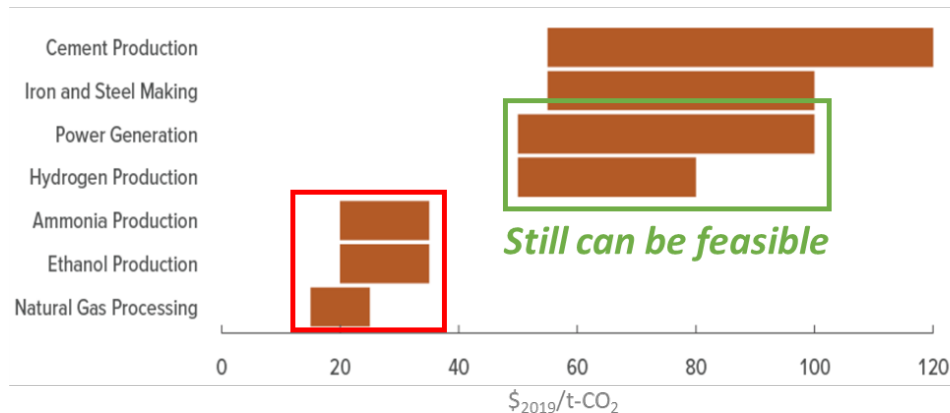
<https://capturacorp.com/technology/>

Separation of CO₂ from Air/Ocean

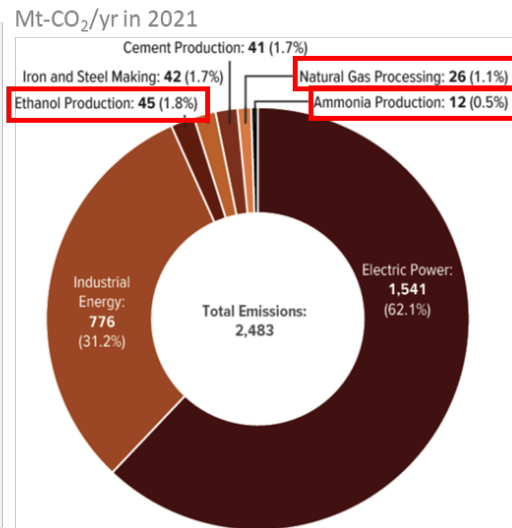


Point-Source CO₂ Capture Costs (*U.S. Data*)

- The cheapest point-source CO₂ capture is for:
 - Ammonia production, ethanol production, and NG processing ← due to high [CO₂] = *easier separation*
- Highest CO₂ emissions come from:
 - Industrial energy and electric power (≈ 93.3%!)



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

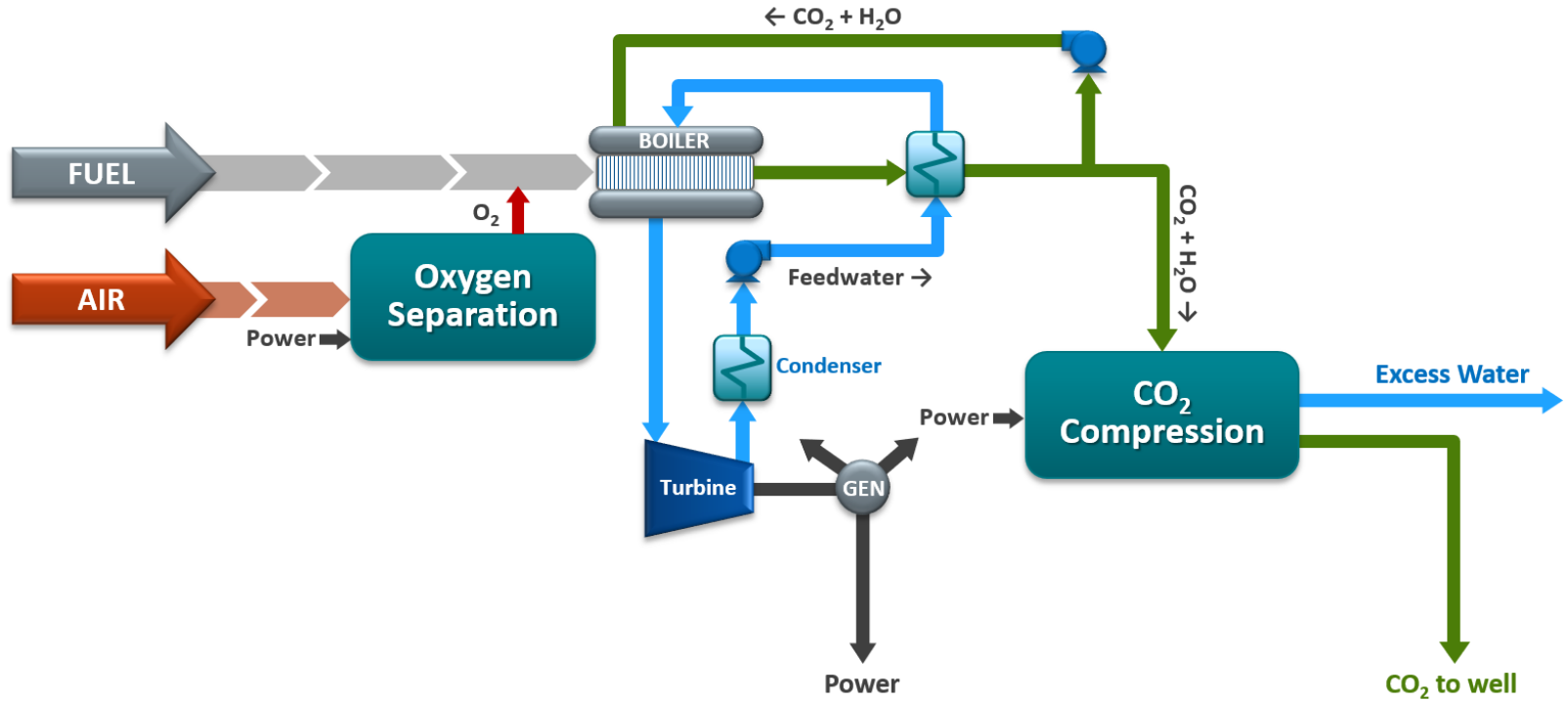


Biogenic CO2 Sources in USA

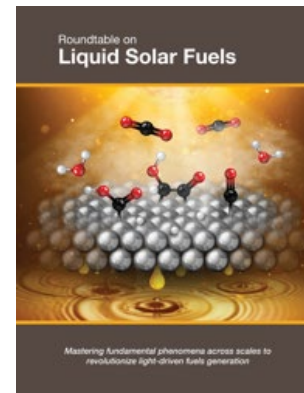
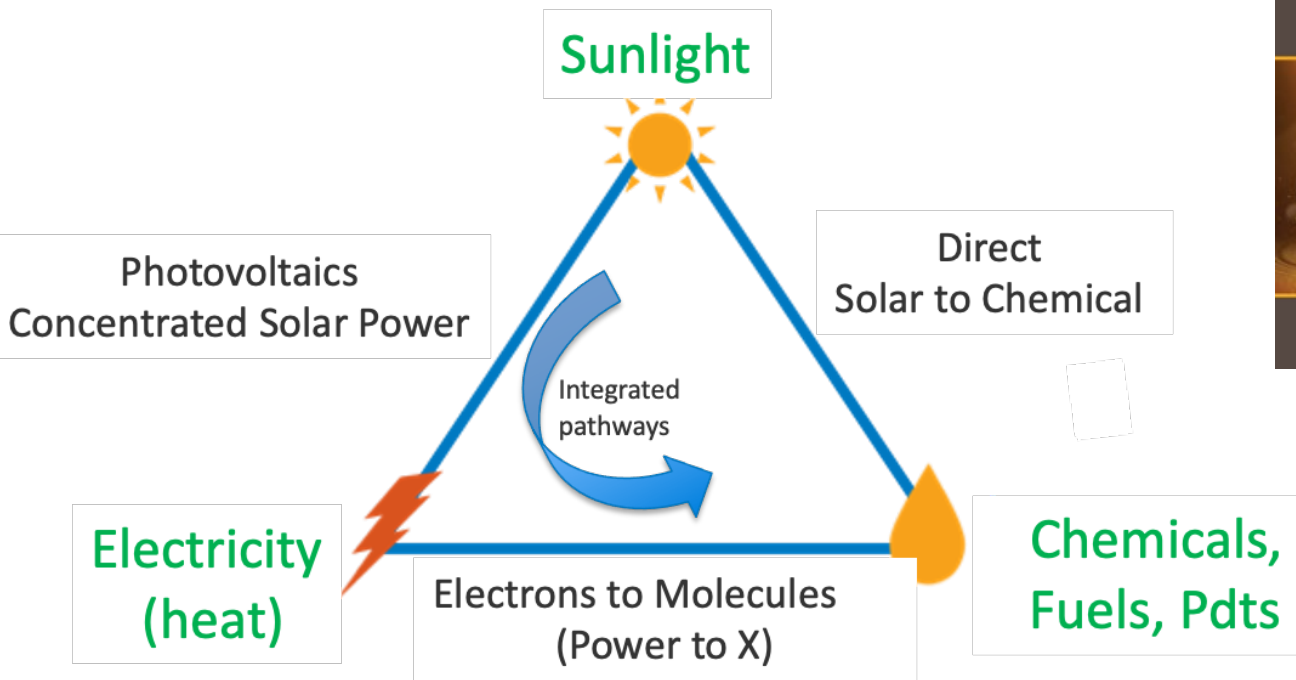
Biogenic CO2 Source	Tons of CO2	Gallons of e-fuels (100 gallons per ton)	
CO2 from Corn Ethanol	41,369,900	4,136,990,000	https://www.sciencedirect.com/science/article/abs/pii/S0360128517300114
Black Liquor Combustion	73,500,000	7,350,000,000	https://www.epa.gov/system/files/documents/2023-02/US-GHG-Inventory-2023-Main-Text.pdf#page122
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>

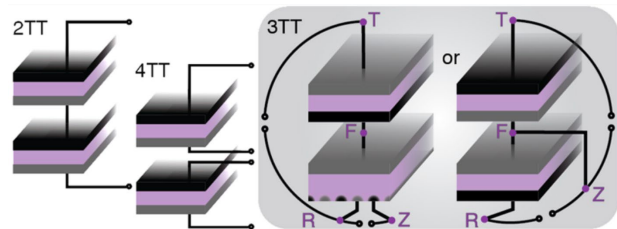
<http://mission-innovation.net/wp-content/uploads/2021/03/Converting-Sunlight-into-Solar-Fuels-and-Chemicals-MI-Challenge-5-roadmap-Feb-2021-final.pdf>



<https://www.liquidsunlightalliance.org>

<https://solarhub.unc.edu/>

Selectivity via co-design in PEC CO₂RR

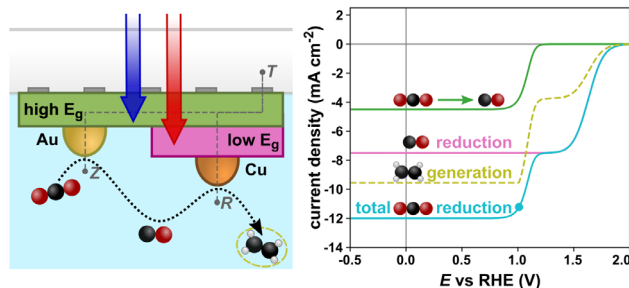
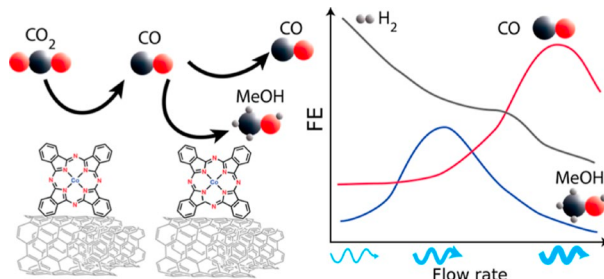


Three-terminal tandems enable multiple potentials

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

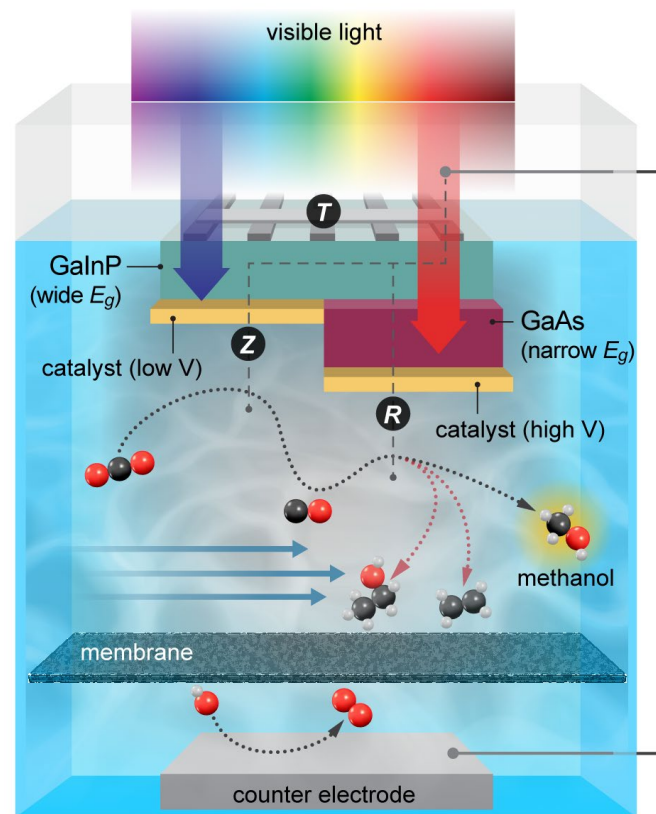
Single catalyst can drive different CO₂RR steps at different potentials

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.

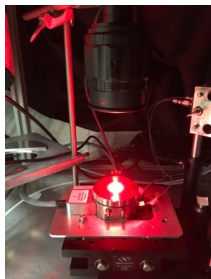


Energy Fuels 2021, 5, 6361–6371.

US Patent 11,961,927 B2, Apr. 16, 2024

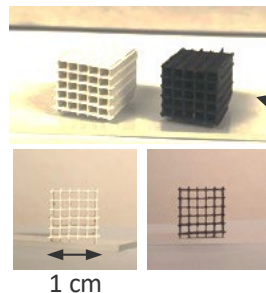
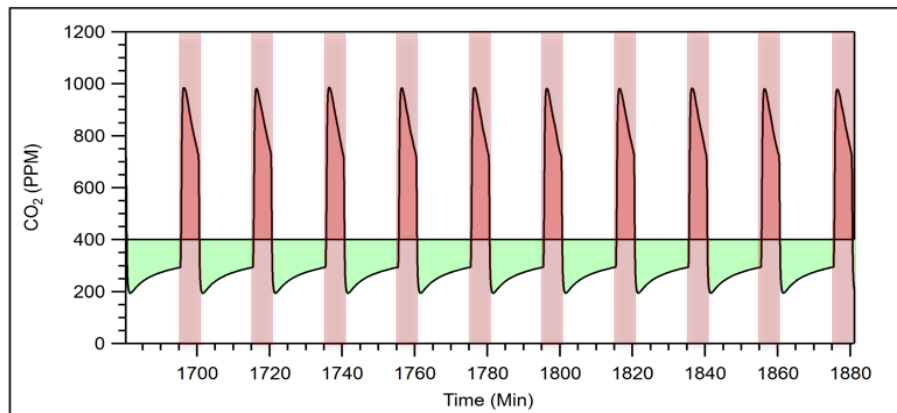
Greenaway et al. *Energy and Fuels* 39, 3703 (2025)

Photo(thermal)-Swing DAC



Aminopolymer-Based Photo-DAC

- Baseline system prior to photo-RCC integration
- Utilizes inexpensive, earth-abundant components (TiO₂ air contactor, TiN absorber)
- Exhibits rapid CO₂ desorption kinetics
- Demonstrated ~90% capacity retention over **2000 cycles**



Visible light absorbing
air contactor w/ plasmonic
Titanium Nitride NPs

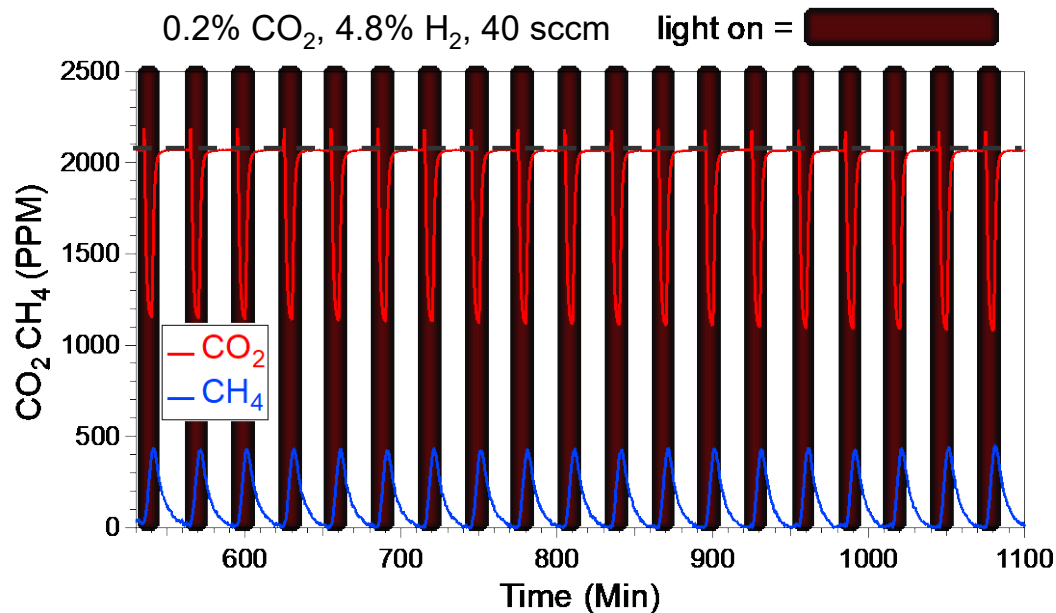
Noemi Leick*, et. al, "Photo-swing CO₂ capture using aminopolymers as sorbents and TiN light absorber", *ACS Sustain. Chem. Eng.*, **2025**, submitted.

[DOI: 10.26434/chemrxiv-2024-b5wji](https://doi.org/10.26434/chemrxiv-2024-b5wji)

Photomethanation of CO₂

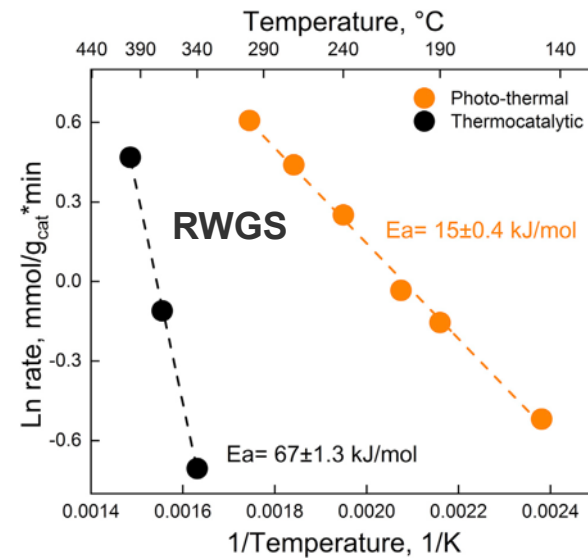
ACS Appl. Energy Mater. 2025, 8, 18, 13179-13184

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.jisci.2022.104107>

Thank you

www.nrel.gov

Randy D. Cortright, Ph.D.

Strategic Lead for Electrons to Molecules

Senior Research Advisor

