Life Cycle Greenhouse Gas Analysis of Direct Air Capture Systems

NATIONAL ENERGY TECHNOLOGY LABORATORY

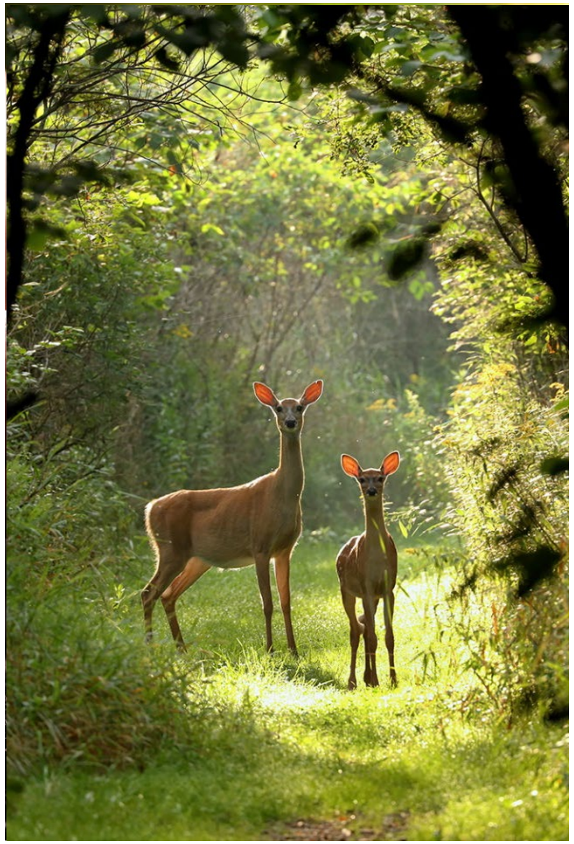
DAC Virtual Kickoff Meeting, February 24-25, 2021
Presented by: Timothy J. Skone, P.E.

What is Life Cycle Assessment/Analysis (LCA)?

LCA is a technique that helps people make better decisions to improve and protect the environment by accounting for the potential impacts from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave).

Why LCA?

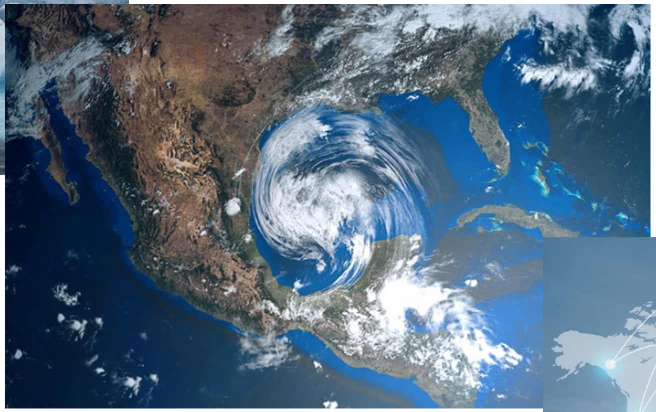
Why what we do is important



Air — Water — Ecosystems — Built Environment

Why LCA?

Driving towards global stewardship



Air — Water — Ecosystems — Built Environment

Why LCA?

Inform Business Decisions: R&D to commercialization (investor confidence)

- **Guide research and development investment**
  we want to invest in emerging technology that is better than we have today

- **Evaluate existing systems to identify opportunities for improvement**
  where should we invest to get the greatest return on investment

- **Identify data gaps and validation needs to improve decision making**
  inform and guide environmental field monitoring activities (data collection)

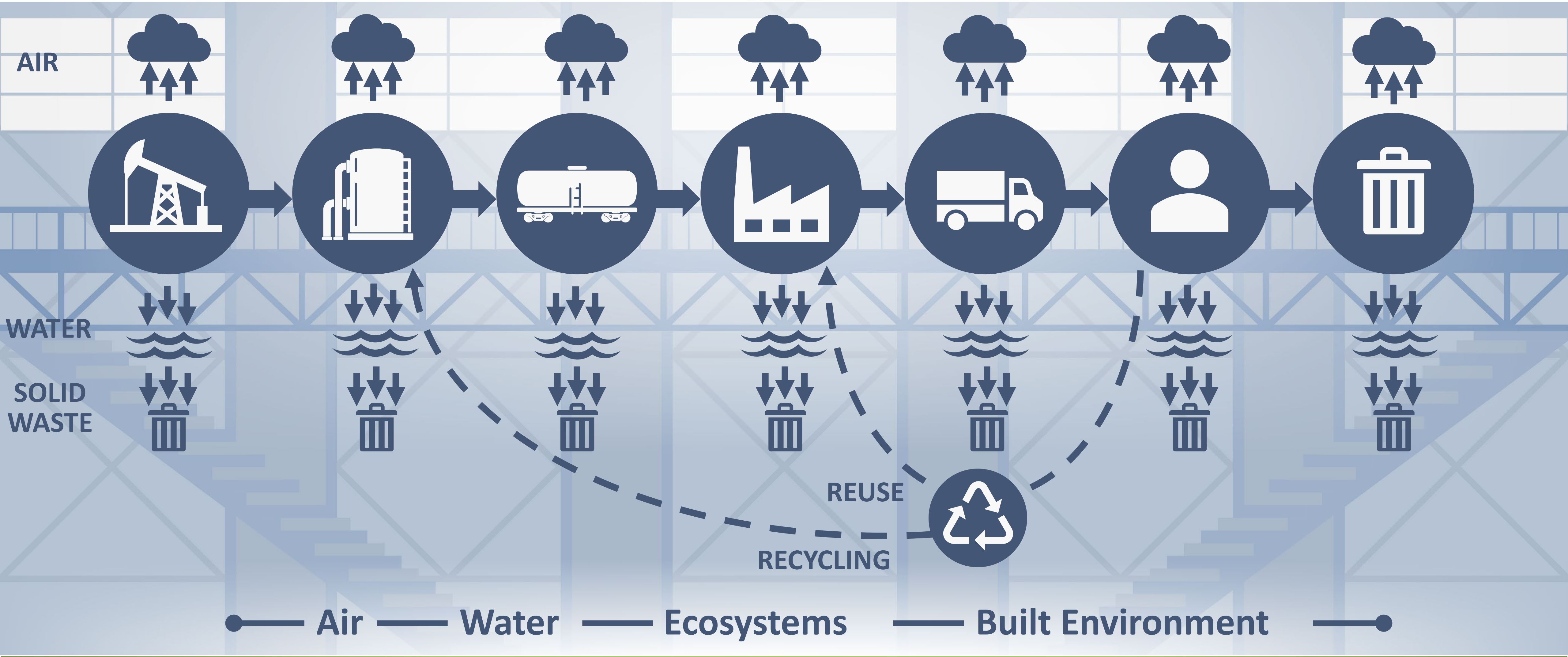
- **Assess benefit potential from technology commercialization**
  quantify the environmental value at varying levels of commercial adoption
  (at what scale will our technology make a measurable difference)

How?

LCA Method

How?

LCA Method



Direct Air Capture (DAC) LCA Questions

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- Under what conditions is **direct air capture (DAC)** carbon negative?
- What is the difference between **carbon negative** and **carbon reducing**?
- What are the GHG implications of carbon utilization for DAC?

Direct Air Capture (DAC)

- **DAC is one of the five IPCC approaches to remove CO_2 from the atmosphere**
  - BECCS, DACCS (shortened to DAC in this work), afforestation & reforestation, and soil carbon sequestration, and enhanced weathering
- **The systems we modeled**
  - Carbon Engineering and a generic sorbent-based system (Fasihi et al.)

System type	CO_2 conc. (ppm)	Binding agents	Heating source	CO_2 (% purity)	Absorption (°C)	Desorption (°C)
Solvent	400	NaOH/KOH & $Ca(OH)_2$	Natural gas	>97	Ambient	900
Sorbent	400	Amine-based material*	Natural gas*	>99	Ambient	100

- For a generic sorbent system, however many different materials are being tested and used (e.g., TRI-PE-MCM-41, MOF(Cr)/MOF(MG), K_2CO_3/Y_2O_3)[DC1] (Fasihi et al., 2019)
- *Fasihi et al. modeled their sorbent based system using Heat pump/ waste heat

Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO2 direct air capture plants. *Journal of Cleaner Production*, *224*, 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086

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Energy Consumption for DAC Systems

Company	Type	Thermal Energy (GJ / t CO_2)	Power (kWH / t CO_2)	Total Energy (GJ)	Reference
Global Thermostat	Sorbent	4.4	160	5.0	(Ishimoto et al., 2017)
Carbon Engineering	**Solvent**	**5.3**	**366**	**6.6**	**(Keith et al., 2018)**
APS 2011 NaOH case	Solvent	6.1	194	6.8	(APS, 2011)
Generic Sorbent	**Sorbent**	**6.3**	**250**	**7.2**	**(Fasihi et al., 2019)**
Climeworks	Sorbent	9.0	450	10.6	(Ishimoto et al., 2017)

Sandalow, D., Friedmann, J., McCormick, C., & McCoy, S. (2018). *Direct Air Capture of Carbon Dioxide* (pp. 1–39). Innovation for Cool Earth Forum. https://www.icef-forum.org/pdf2018/roadmap/ICEF2018_DAC_Roadmap_20181210.pdf

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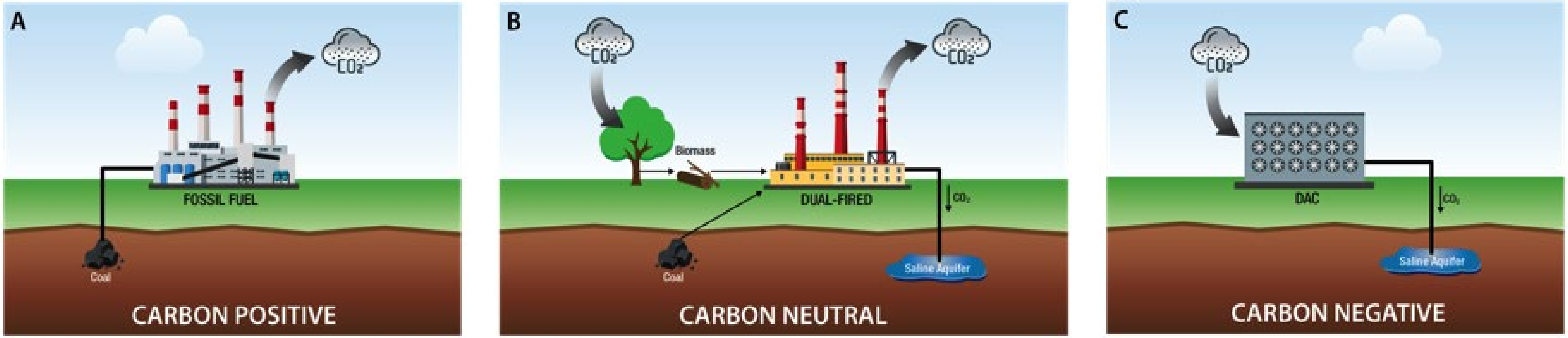
APS. (2011, June 1). *Direct Air Capture of CO2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs*. https://www.aps.org/policy/reports/assessments/upload/dac2011.pdf

Is DAC Carbon Negative?

Life Cycle Carbon Equivalent Accounting Designation for GHG Mitigation

In isolation, is a system carbon positive, neutral, or negative?

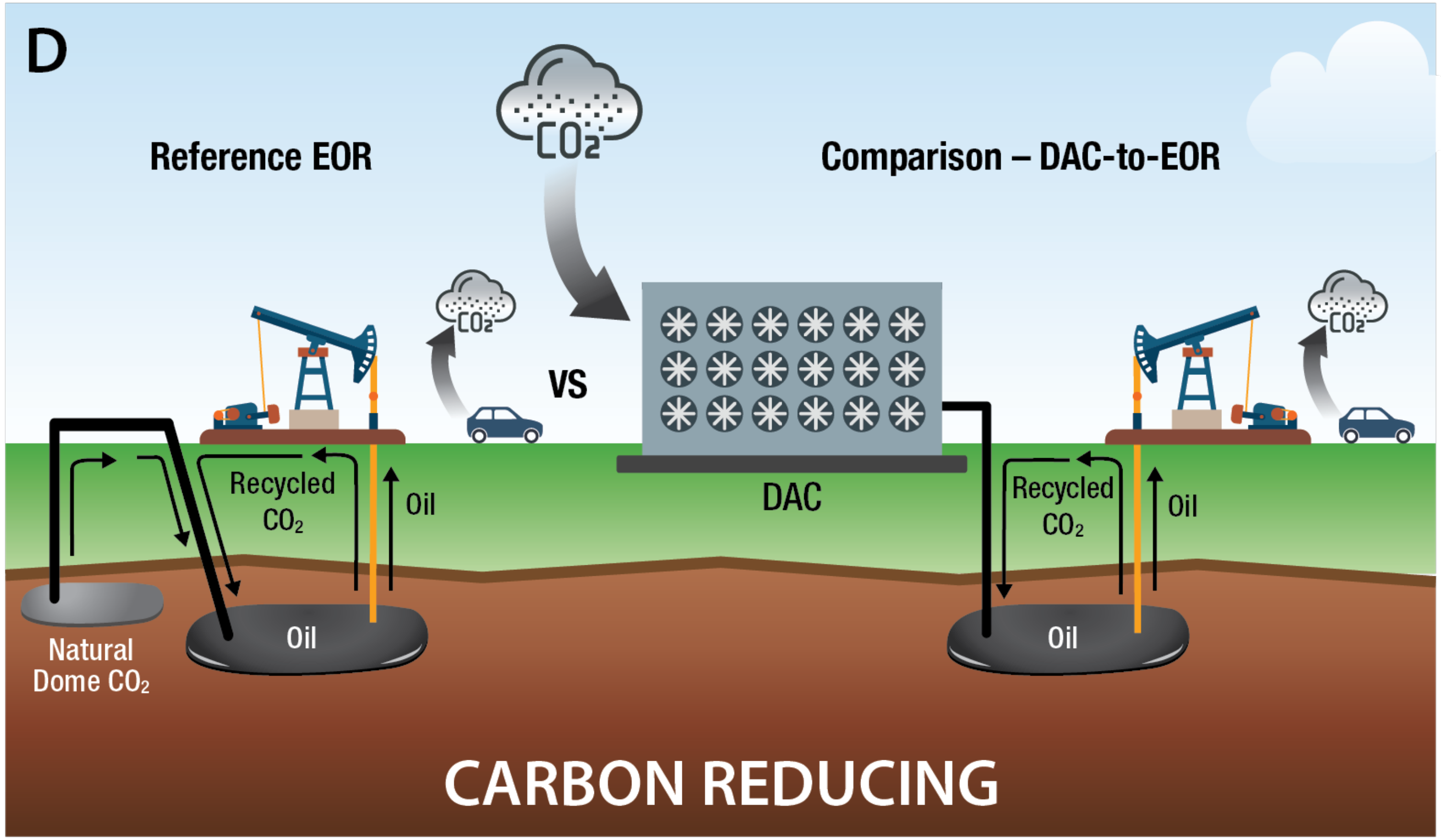


Assumed that biomass in this case is harvested sustainably

Is DAC Carbon Reducing?

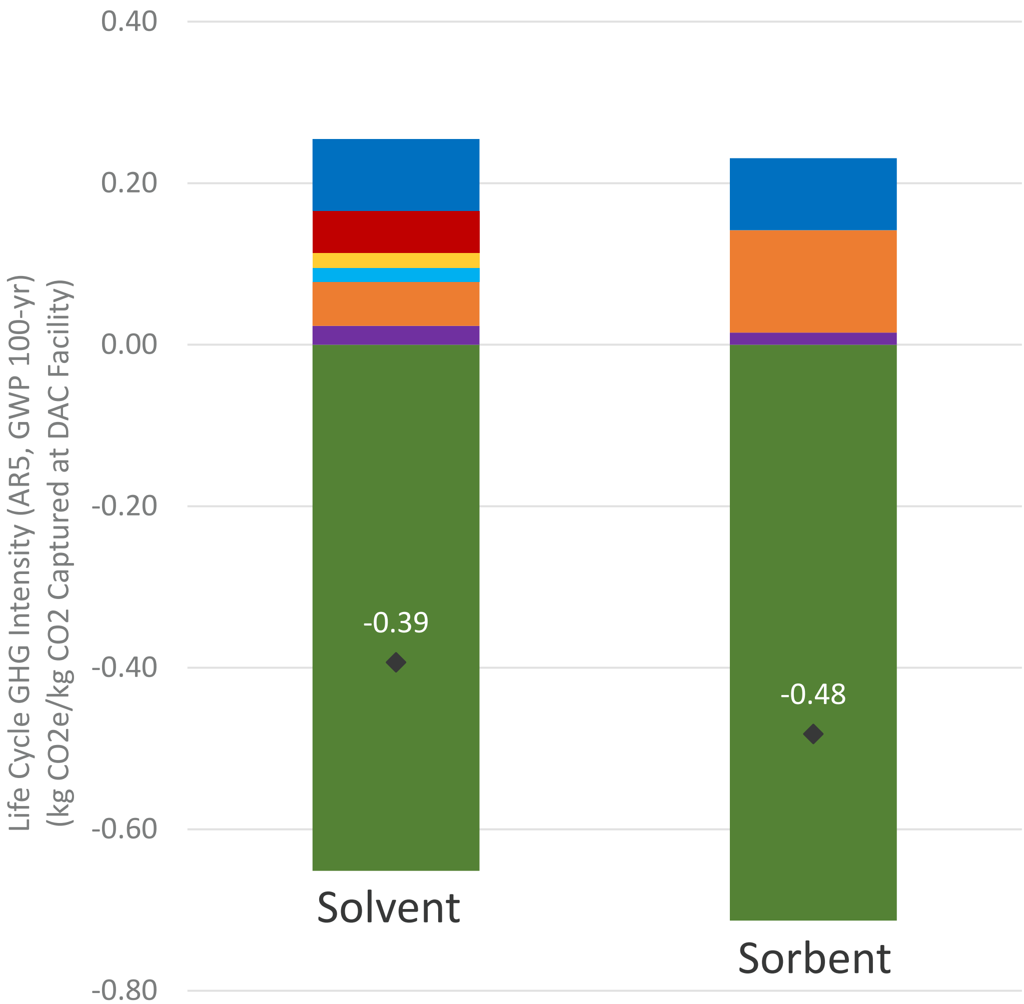
Carbon Positive Systems can be Carbon Reducing to a Comparison System

Does a system reduce total carbon emissions relative to comparison system?



Net GHG for DAC Systems by Process

Direct Air Capture Produces Negative Emissions, Cradle-to-Gate



	Solvent	Sorbent
Auxiliary *	<0.01	<0.01
Compressor (CO_2 Product)	0.09	0.09
Air Separation Unit	0.05	
Slaker	0.02	
Calciner (Natural Gas)	<0.01	
Pellet Reactor	0.02	
Air Contactor	0.05	0.13
Natural Gas (Upstream)	0.02	0.01
Calcium Carbonate (Upstream)	<0.01	
Potassium Hydroxide (Upstream)	<0.01	
Water		
Mass of Atmospheric CO_2 **	-0.65	-0.71
◆Total	-0.39	-0.48

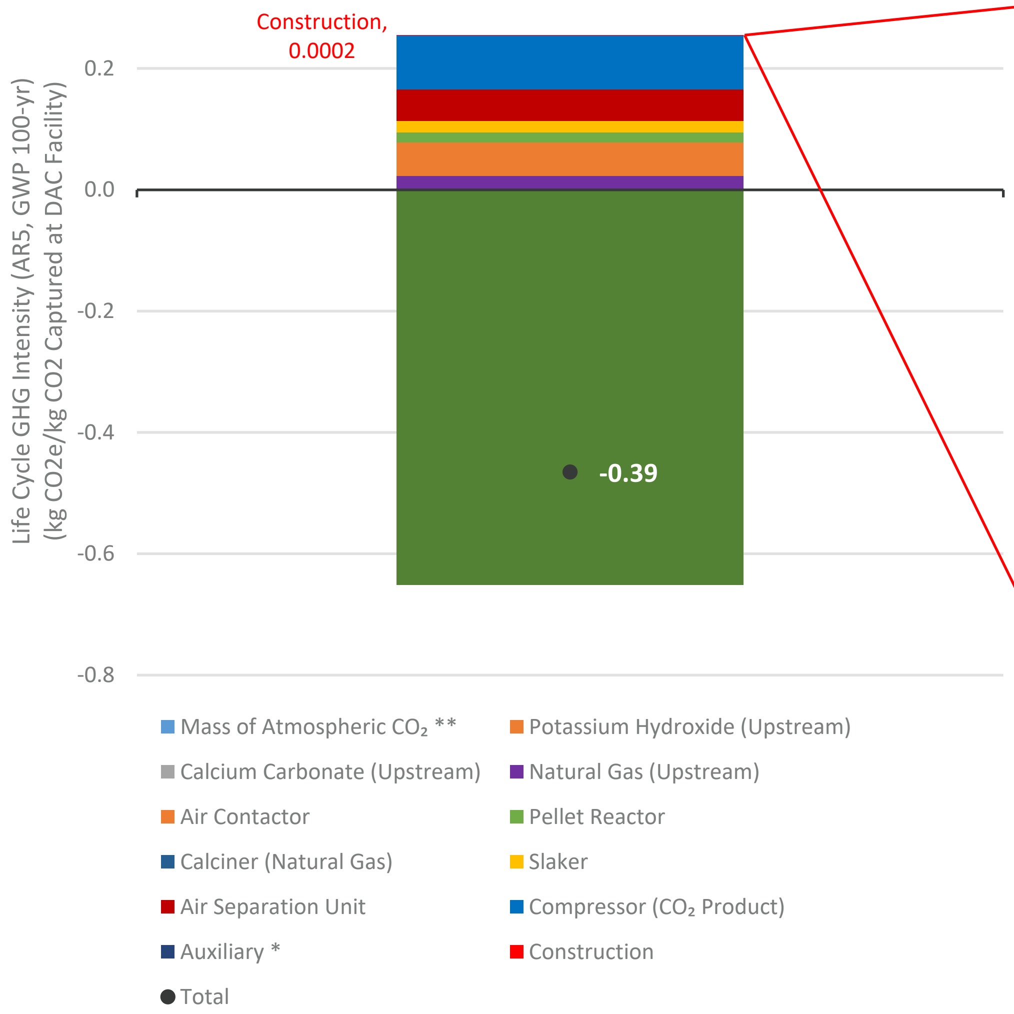
* Auxiliary loads consist of circulating water pumps, cooling tower fans, CO_2 capture and removal auxiliaries (for natural gas boiler), CO_2 compression (for natural gas boiler), feedwater pumps, ground water pumps, selective catalytic reduction (attached to the natural gas boiler for flue gas treatment), and miscellaneous plant balance.

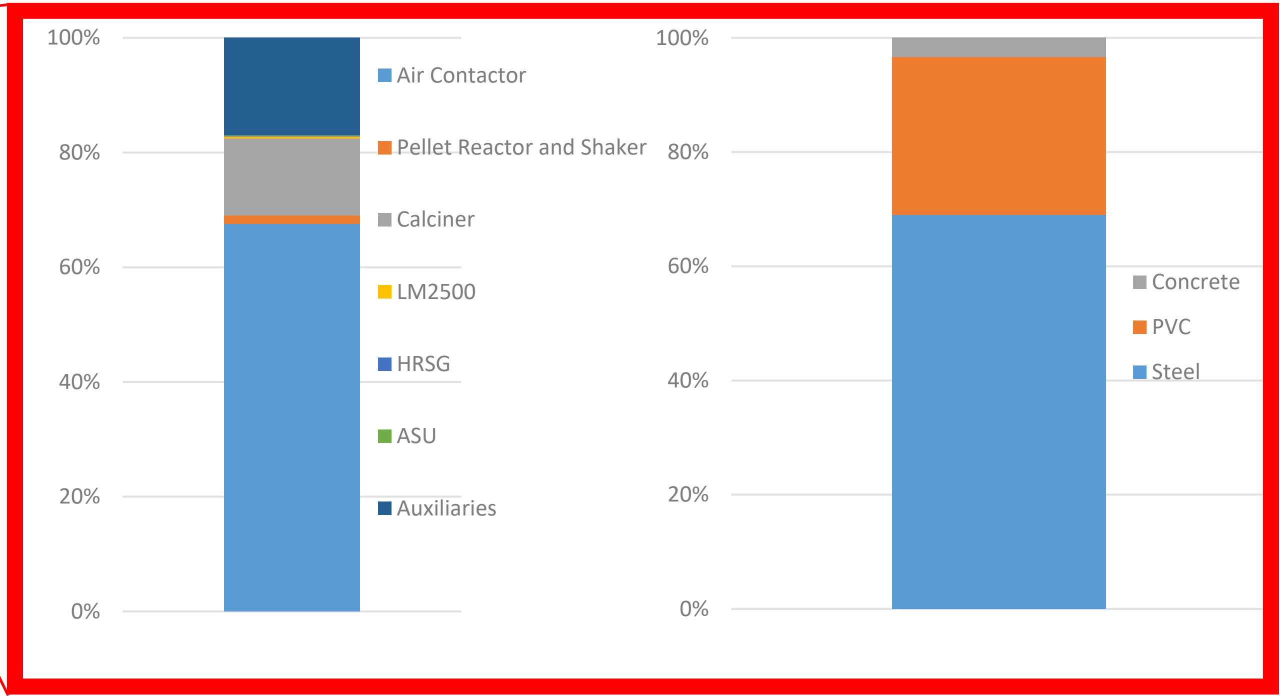
** The Mass of Atmospheric CO_2 is less than 1 kg because a portion of the kg of CO_2 product is captured from natural gas combustion onsite and not removed from the atmosphere.

These values represent uncertain point estimates of nascent technology that may significantly change with development

Embodied Carbon Emissions - Construction

DAC Solvent System, 1 MT CO2 capture capacity/year, 20-year Service Life (estimate)





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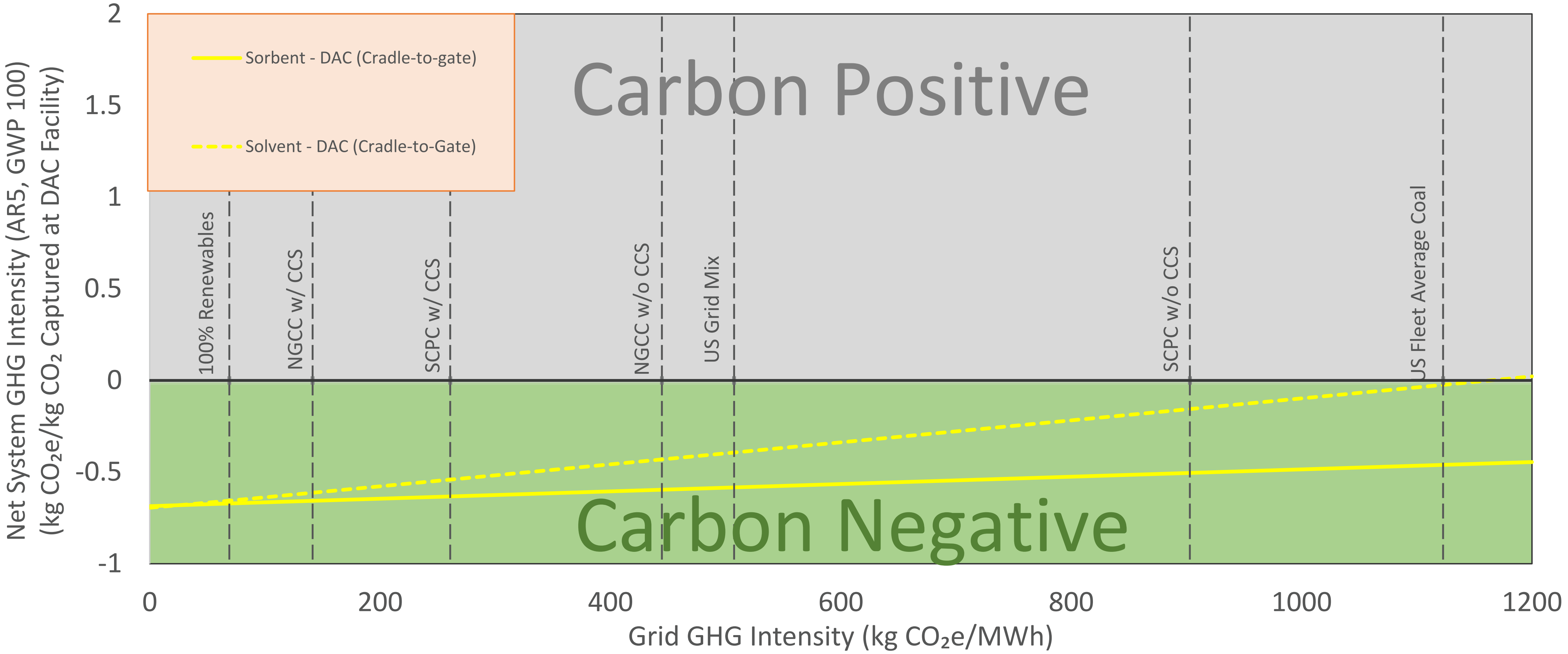
DAC – Cradle-to-Gate GHG Emissions

Is the system carbon negative, cradle-to-gate?



Y-axis values below zero indicate life cycle carbon negative emissions. Results that are greater than zero indicate life cycle carbon positive emissions, as these results indicate that they emit more CO_2 than is removed from the atmosphere.

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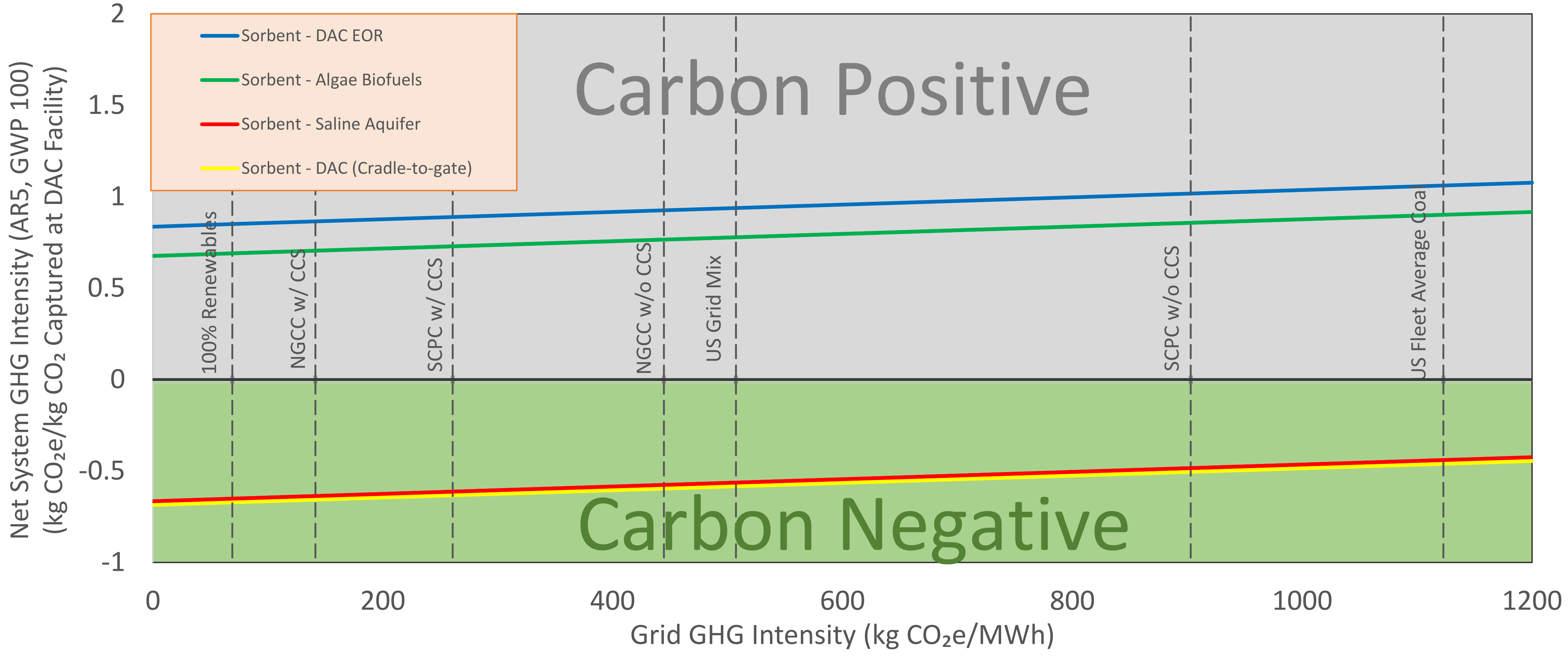
Sorbent-based DAC – Net GHG Emissions

Cradle-to-Grave Impacts for Saline Aquifer Storage, EOR, & Algae Biofuel Production



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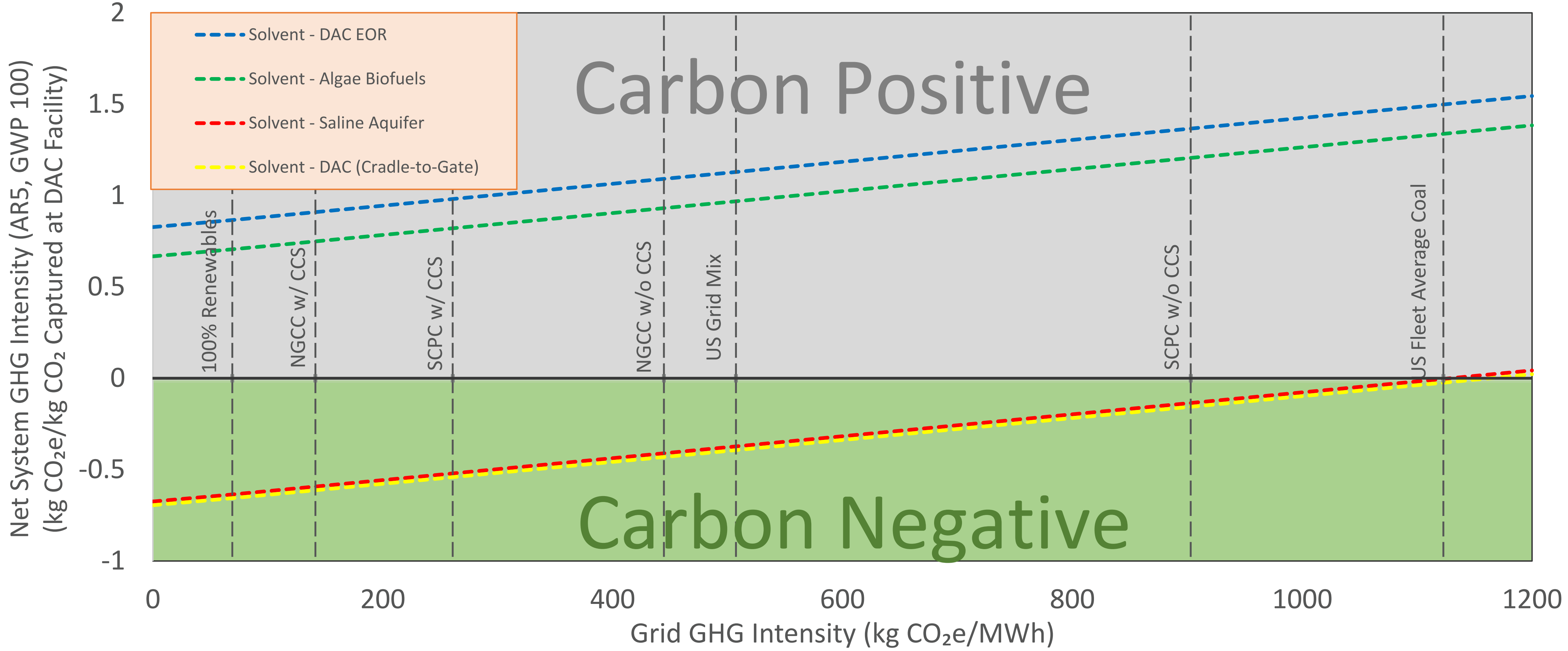

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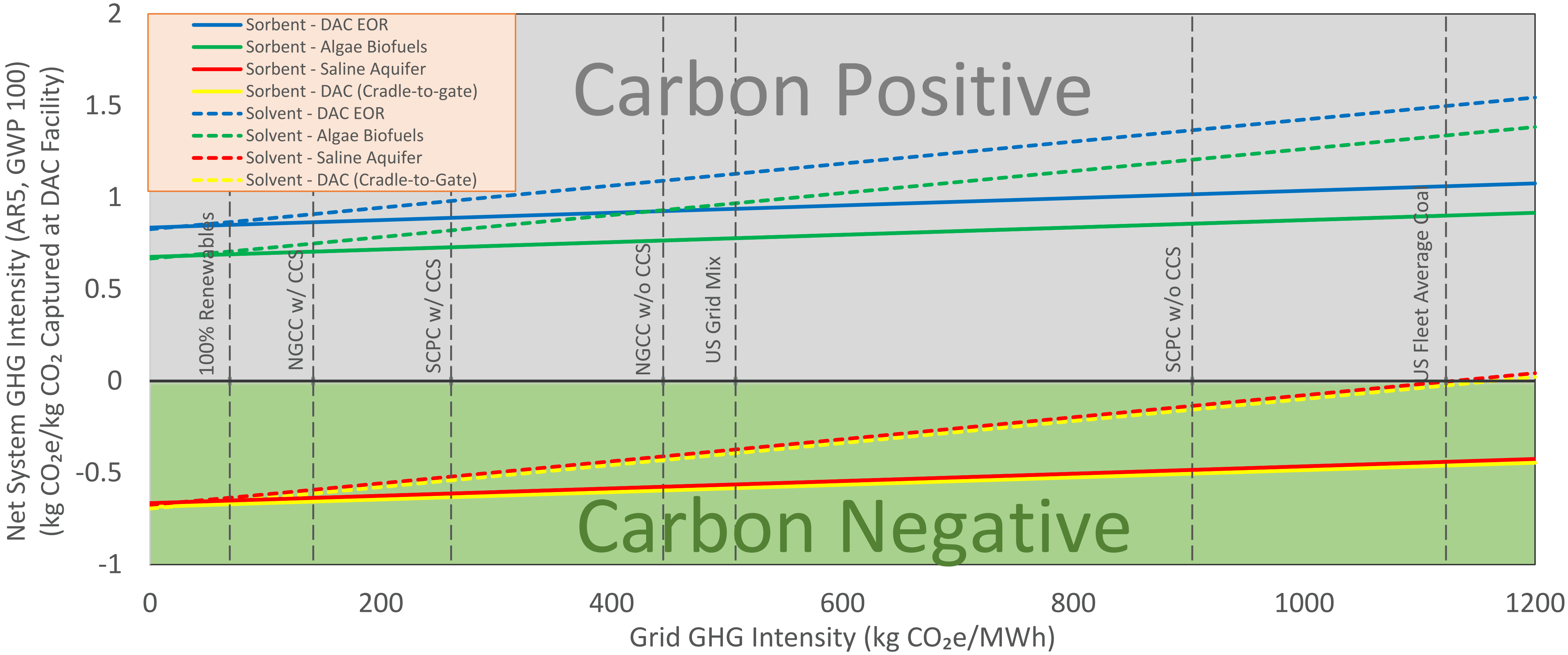

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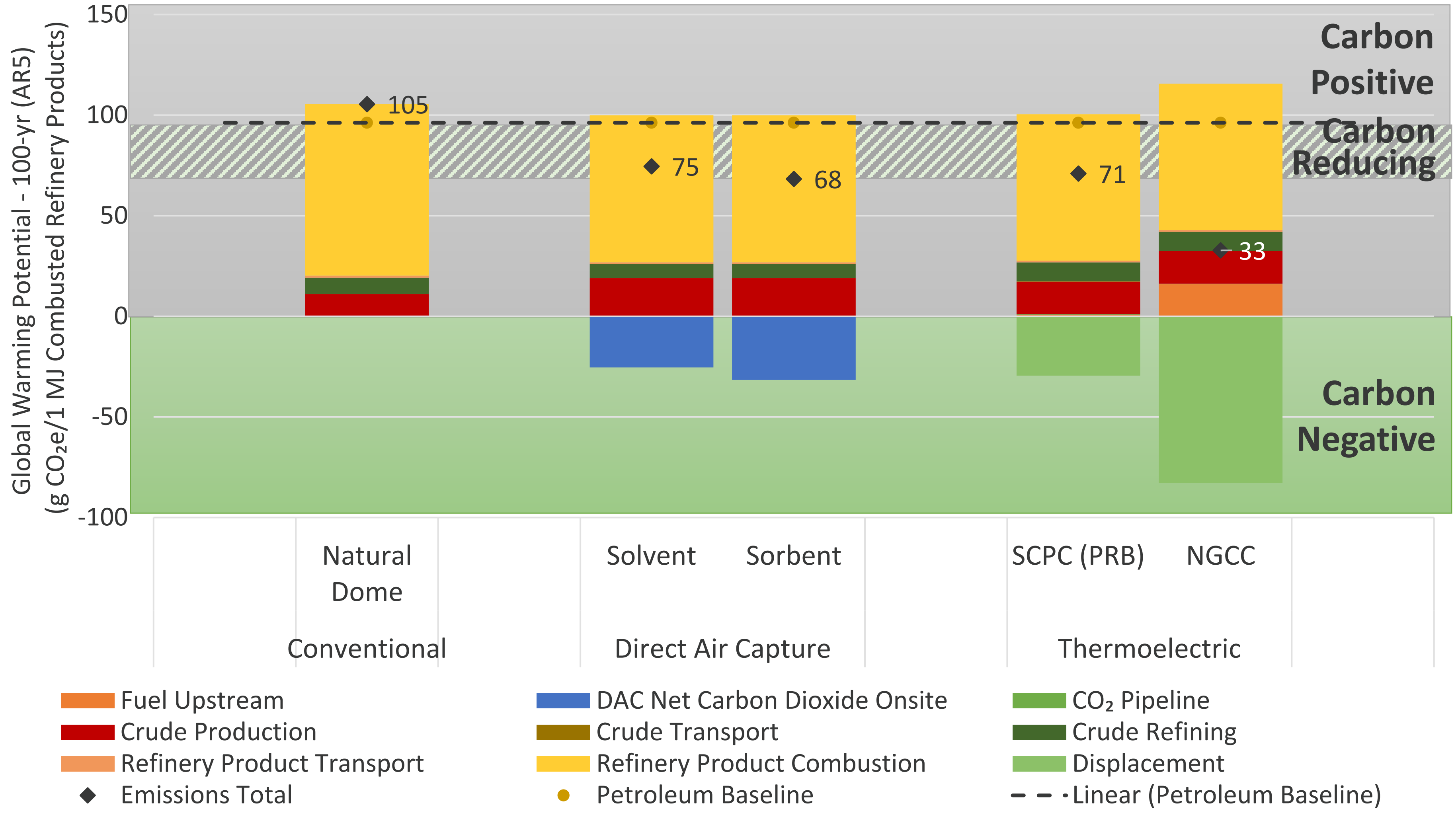
DAC-to-Enhanced Oil Recovery (EOR)

DAC-EOR Outperforms Natural Dome EOR but not Thermoelectric-EOR



- DAC-to-EOR produces less GHG emissions than the BAU Petroleum Baseline
- DAC-to-EOR is Carbon Reducing
- Carbon sourced from thermoelectric capture can be environmentally favorable to DAC CO_2

These values represent uncertain point estimates of nascent technology that may significantly change with development

Discussion and Conclusions

Revisiting the original questions

- Under what conditions is **direct air capture (DAC)** carbon negative?
  - ***Direct air capture with saline aquifer storage is carbon negative***
- What is the difference between **carbon negative** and **carbon reducing**?
  - ***Carbon negative indicates a physical removal of carbon dioxide from the atmosphere***
  - ***Carbon reducing indicates a lower greenhouse gas emission than a reference system***
- What are the GHG implications of carbon utilization for DAC?

Discussion and Conclusions

What are the GHG implications of carbon utilization for DAC?

- **DAC-to-Saline aquifer storage removes CO_2 from the atmosphere**
  - Solvent-based DAC net emissions are -0.39 kg CO_2e per kg captured
  - Sorbent-based DAC net emissions are -0.48 kg CO_2e per kg captured
  - This technology pathway is **carbon negative**

- **DAC-to-EOR is carbon reducing**
  - System-wide emissions are 28%-36% lower than conventional EOR
  - System still produces positive emissions to the environment

FOA 2188: Appendix F – Pre-screening LCA

Overview of LCA Requirements for AOI-2

- **A Pre-screening Life Cycle Analysis (LCA) is required for AO1-2.**
  - LCA is not required for AOI-1.
- **What does "pre-screening" mean?**
  - Reduced reporting requirements – greater uncertainty expected.
  - Minimum requirement is the accounting of greenhouse gas emissions (reduced life cycle inventory scope, additional reporting of non-GHG is encouraged, but not required)
  - No specific LCA modeling requirements or reporting template required per the FOA.
- **Two LCA Modeling Options based on the fate of the CO_2 product:**
  - Option 1: Sent to Saline Storage for Permanent Sequestration
  - Option 2: Utilized to Make a Product

FOA 2188: Appendix F: LCA Option 1

Option 1: Sent to Saline Storage for Permanent Sequestration

- **System Boundary: Cradle-to-Gate**
  - Cradle = Capture of CO_2 from atmosphere and full life cycle upstream profiles for:
    - Electricity input to DAC facility - 4 scenarios pre-defined in Appendix F
    - Life cycle supply chains for all non-electricity energy inputs, chemical inputs, and significant construction and equipment manufacturing materials (e.g., structural steel, concrete, etc.)
  - Gate = exit of DAC facility, compressed CO_2 (2,200 PSI), pipeline ready for transport
  - Modeling of CO_2 transport and saline storage operations are not required.
    - Results shall be reported for each of the 4 scenarios pre-defined in Appendix F and excluding CO2 product transport and storage operations.
- **LCA Results Reporting (Functional Unit):** 1 kg of captured, compressed, pipeline-ready CO_2 [kg CO_2e/kg CO_2]

FOA 2188: Appendix F: LCA Option 2

Option 2: Utilized to Make a Product

- **System Boundary: Cradle-to-Grave**
  - Cradle = Capture of CO_2 from atmosphere and full life cycle upstream profiles for:
    - Electricity input to DAC facility, life cycle supply chain based on modeled location of DAC facility
    - Life cycle supply chains for all non-electricity energy inputs, chemical inputs, and significant construction and equipment manufacturing materials (e.g., structural steel, concrete, etc.)
  - Grave = Use and end-of-life of CO_2-derived product based on the service provided to society
  - Modeling must compare a proposed product system to an appropriate comparison product system using a multiproduct functional unit and system expansion.
- **LCA Results Reporting (Functional Unit):** Based on the service provided by the CO_2-derived product(s) [will be unique for each project]
  - See NETL CO2U LCA Guidance Toolkit for additional guidance and resources: www.netl.doe.gov/LCA/CO2U

FOA 2188: Appendix F – Pre-screening LCA

General Resources and GWP Values

- **DOE/NETL LCA Resources (www.netl.doe.gov/LCA/CO2U)**
  - General LCA guidance - CO2U LCA Guidance Document
  - NETL Life Cycle Inventory Data – NETL CO2U openLCA LCI Database
  - Electricity Consumption LCI Data – NETL Grid Mix Explorer
    - www.netl.doe.gov/LCA see Models and Tools section
- **Global Warming Potential Values**

GHG	AR5 (IPCC 2013)[1]	
	20-year	100-year (Default)
Carbon Dioxide (CO_2)	1	1
Methane (CH_4)	85	36
Nitrous Oxide (N_2O)	264	265
Sulfur Hexafluoride (SF_6)	17,500	23,500

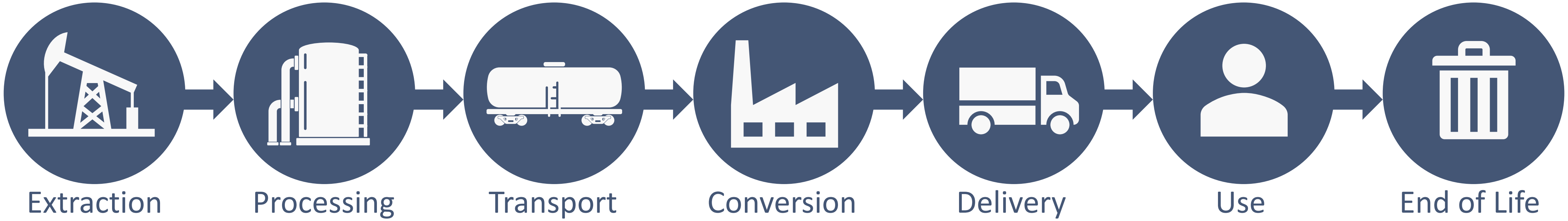
[1] IPCC. (2013). *Climate Change 2013 The Physical Science Basis*. New York: Cambridge University Press: Intergovernmental Panel on Climate Change Retrieved December 12, 2013, from https://www.ipcc.ch/report/ar5/wg1/

The NETL CO2U LCA Guidance Toolkit

- Supports funding recipients with their LCA requirements
- Simplifies the process of LCA
- Improves consistency in communicating results
- Toolkit site: www.netl.doe.gov/LCA/CO2U

Energy Life Cycle Analysis (LCA)

Cradle-to-grave environmental footprint of energy systems



Mission

Evaluate existing and emerging energy systems to guide R&D and protect the environment for future generations

Vision

A world-class research and analysis team that integrates results that inform and recommend sustainable energy strategy and technology development

LCA
Life Cycle Analysis
• energy sustainability •

NETL Publications, Models, and Data available at:

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Over 200 publications and 500 unit process data files

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Life Cycle Analysis
energy sustainability

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DISCLAIMER

Attribution

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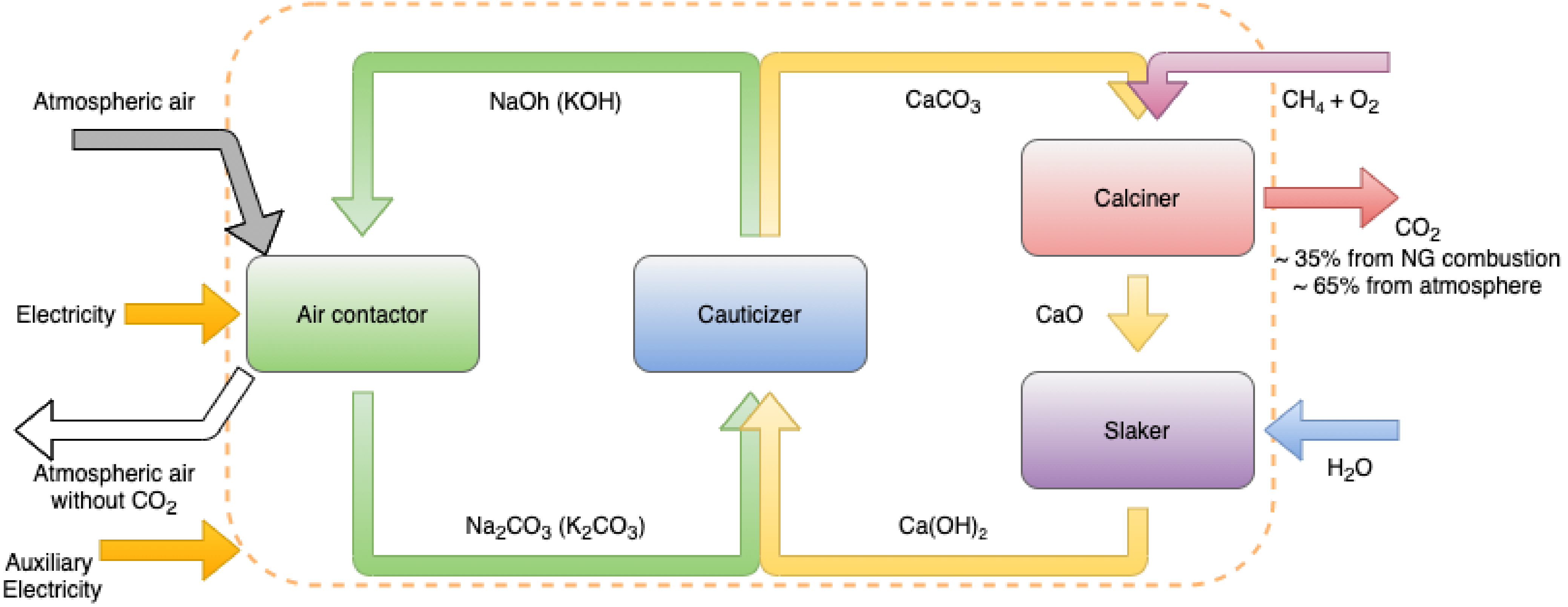
Backup Slides

Solvent-Based DAC Flow Diagram



Carbon Engineering Solvent DAC System Flow Diagram (Fasihi et al., 2019)

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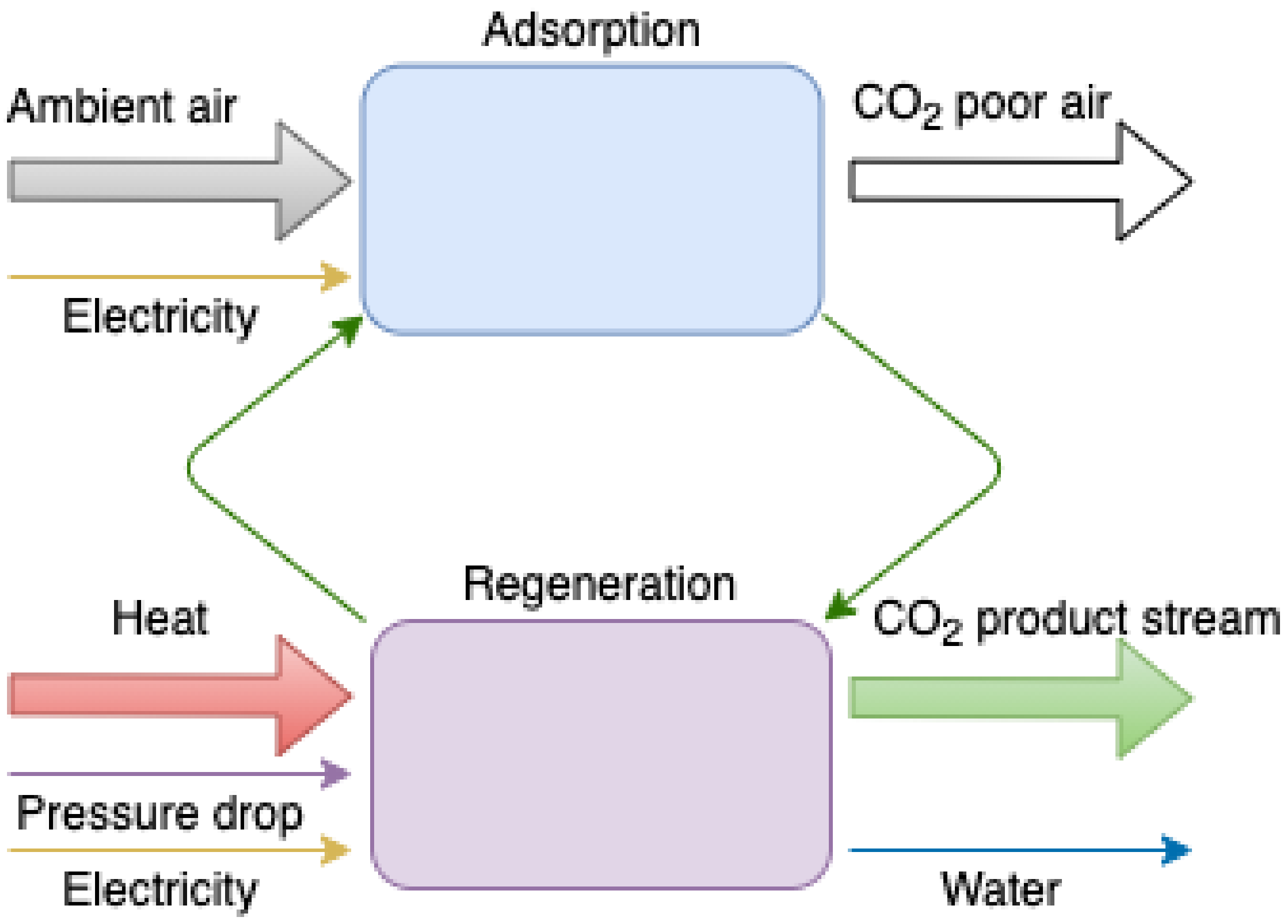
Sorbent-Based DAC Flow Diagram



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Fasihi et al. Sorbent Systems

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Table 2
LT solid sorbent DAC specifications.

sorbent	CO_2 con.	adsorption	desorption		energy demand			cooling		CO_2 purity	reference
	ppm	T (°C)	T (°C)	P (bar)	kWh_{el}/t	kWh_{th}/t	by	T (°C)	by	%	
amine-based	400	ambient	100	0.2	200–300	1500–2000	waste heat	15	air/water	99.9	Climeworks (2018b); Vogel (2017)
amino-polymer	400	ambient	85–95	0.5–0.9	150–260	1170–1410	steam	ambient	water evaporation	>98.5	Ping et al. (2018b) (Global Thermostat)
TRI-PE-MCM-41	400	ambient	110	1.4	218	1656	steam	–	–	88	Kulkarni and Sholl (2012)
MOF (Cr)	400	ambient	135–480	1	1420		HT steam	–	–	–	Sinha et al. (2017)
MOF (MG)	400	ambient	135–480	1	997		HT steam	–	–	–	
K_2CO_3/Y_2O_3	400	ambient	150–250	–	–	–	el. heater	–	–	–	Derevschikov et al. (2014)
K_2CO_3	–	ambient	80–100	–	694	2083	waste heat	ambient	airflow	–	Roestenberg (2015); Antecy (2018)
-	**400**	**ambient**	**100**	–	**250**	**1750**	**heat pump/waste heat**	–	–	**>99**	**final model (this study)**

Fasihi et al. Solvent Systems

Table 1
HT aqueous solution DAC specifications.

type	1st cycle sorbent	2nd cycle sorbent	CO_2 con.	absorption	desorption	energy demand			outlet pressure	CO_2 purity	reference
			ppm	T (°C)	T (°C)	kWh_{el}/t	kWh_{th}/t	by	bar	%	
2-cycle	NaOH	$Ca(OH)_2$	-	ambient	900	-	-	NG	100	-	Keith et al. (2006)
	NaOH	$Ca(OH)_2$	500	ambient	900	440	1678	NG	58	-	Baciocchi et al. (2006)
	NaOH	$Ca(OH)_2$	380	ambient	900	764	1420	NG/coal	-	-	Zeman (2007)
	NaOH	$Ca(OH)_2$	-	-	900	$1199\text{-}2461_{el,th}$ [a]		-	-	-	Stolaroff et al. (2008)
	NaOH	$Ca(OH)_2$	500	-	900	494	2250	NG	100	-	Socolow et al. (2011)
	NaOH	$Ca(OH)_2$	-	ambient	900	2790	-	wind + battery [b]	-	-	Li et al. (2015) [c]
	KOH	$Ca(OH)_2$	-	-	900	-	2780	NG [d]	150	-	Carbon Engineering (2018c)
	KOH	$Ca(OH)_2$	-	-	900	1500	-	el.	150	-	
	KOH	$Ca(OH)_2$	400	ambient	900	-	2450	NG	150	97.1	Keith et al. (2018)
	KOH	$Ca(OH)_2$	400	ambient	900	366	1458	NG + el.	150	97.1	(Carbon Engineering)
	KOH	$Ca(OH)_2$	400	ambient	900	77 [e]	1458	NG + el.	1	97.1	
	NaOH	$Na_2O.3TiO_2$	-	ambient	850	-	[f]	-	15 [g]	pure	Mahmoudkhani and Keith (2009)
1-cycle	-	CaO	500	365-400	800-875	-	-	CSP	-	99.9	Nikulshina et al. (2009)
2-cycle	**KOH**	**$Ca(OH)_2$**	**400**	**ambient**	**900**	**1535**	-	**el.**	**1**	**>97**	**final model (this study)**

[a] Based on different contactors
[b] Based on Zeman (2007), without heat recycling.
[c] The heat generation method not available.
[d] Heat and electricity generation ratio not available.
[e] Air separation unit and CO_2 compressor excluded.
[f] 50% less high-grade heat than conventional causticisation.
[g] CO_2 separation at 15 bar and then compression to 100 bar.