Life Cycle Analysis at NETL

2020 Integrated Project Review Meeting

Carbon Capture: October 7, 2020

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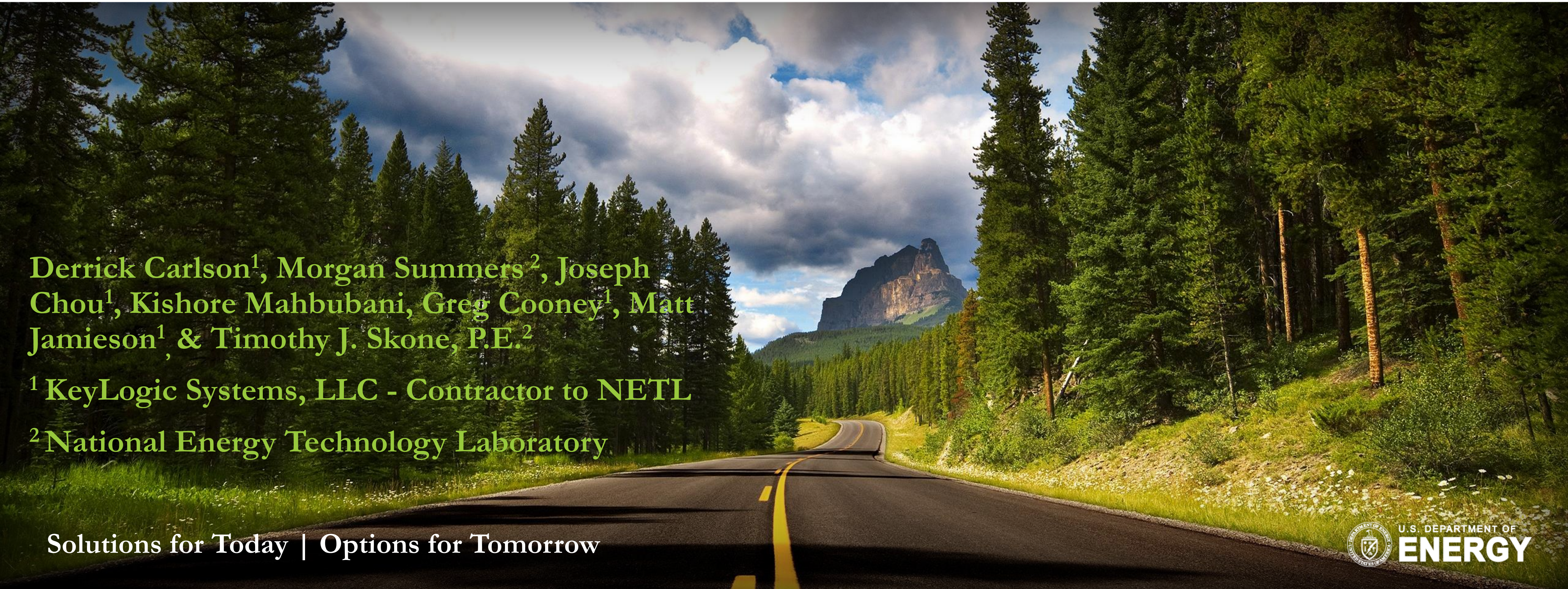

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Solutions for Today | Options for Tomorrow

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Attribution

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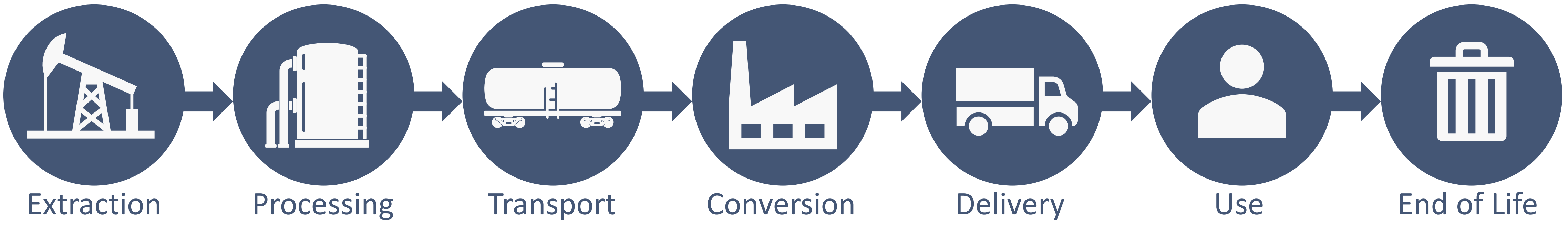
Presentation Outline

- **General - Role of LCA, what does it do for you?**
- **Program specific Accomplishments - What have we produced?**
  - What insight did we gain from this? What are the key takeaways from this work?
- **Future work**
  - Public acceptance, communication, outreach - create momentum around an idea
  - Inform future program direction/investments based on the comparison of different technology options, while evaluating the potential for tradeoffs

Energy Life Cycle Analysis (LCA)

Cradle-to-Grave Environmental Footprint of Energy Systems



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).

Value of LCA to the Capture Program

Understanding the Environmental Burdens of Energy with and without Capture

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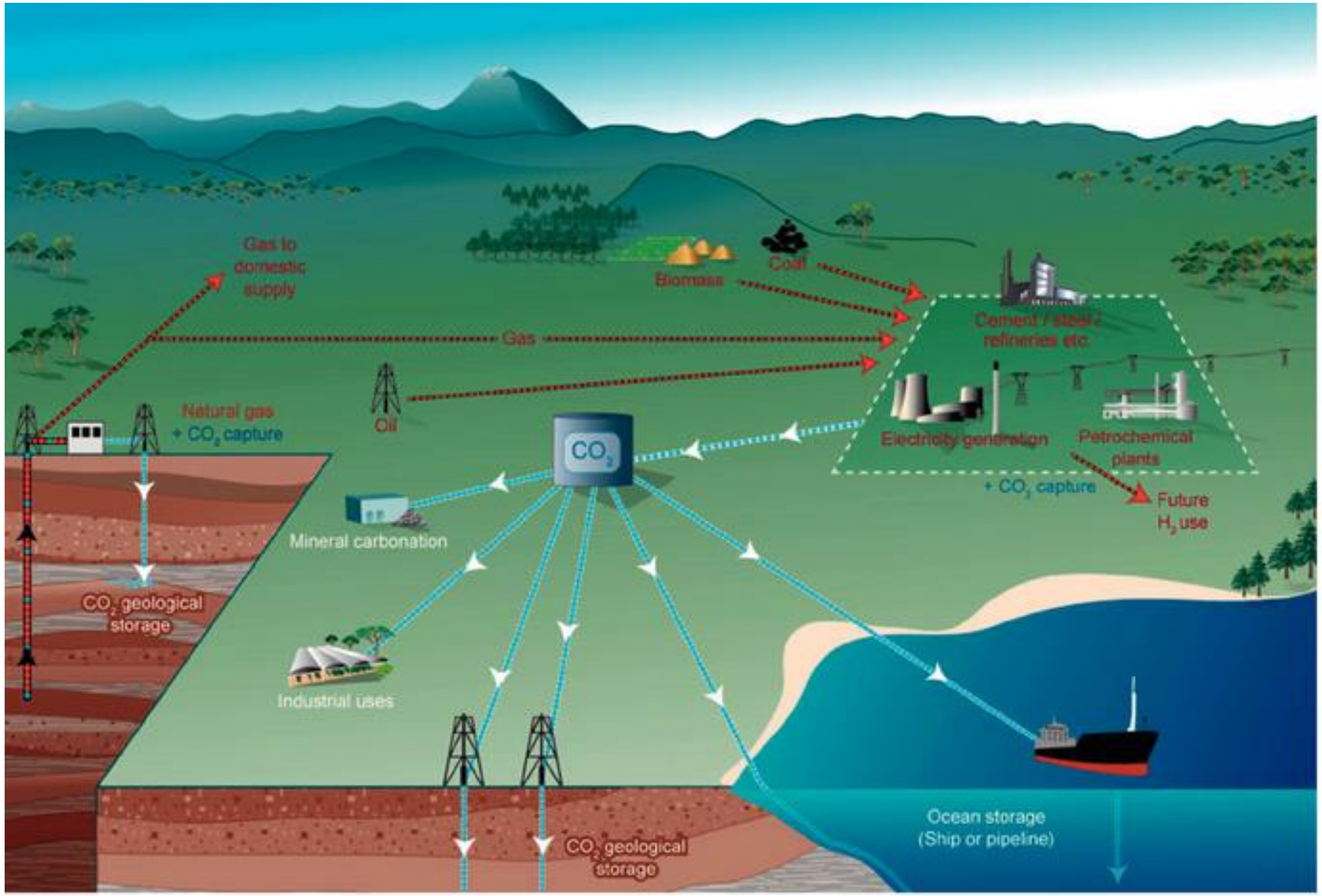
- **LCA offers important information on the environmental impacts of carbon capture beyond reduced greenhouse gas emissions**
  - Helps focus DOE, industry, and policy makers on areas where carbon capture can be the most beneficial
  - Identifies potential hotspots where carbon capture can be improved
- **LCA helps to quantify the full environmental impacts of energy systems with and without capture**
  - Understanding the differences between energy sources with and without carbon capture will be vital for its implementation and scale up in the future
  - Findings can help inform the most beneficial uses of capture and can link to other analytical methods (e.g., TEA) to provide a cost for life cycle carbon mitigation

Relevance of CCS and Potential Sources

LCA can Help us to Select Amongst an Array of Options

Applications Covered

- Thermoelectric Capture
- “Petra Nova Style” Capture
- Industrial Capture
  - Ammonia Production
  - Petroleum Refining
- Direct Air Capture (DAC)
- Bioenergy with CCS (BECCS)

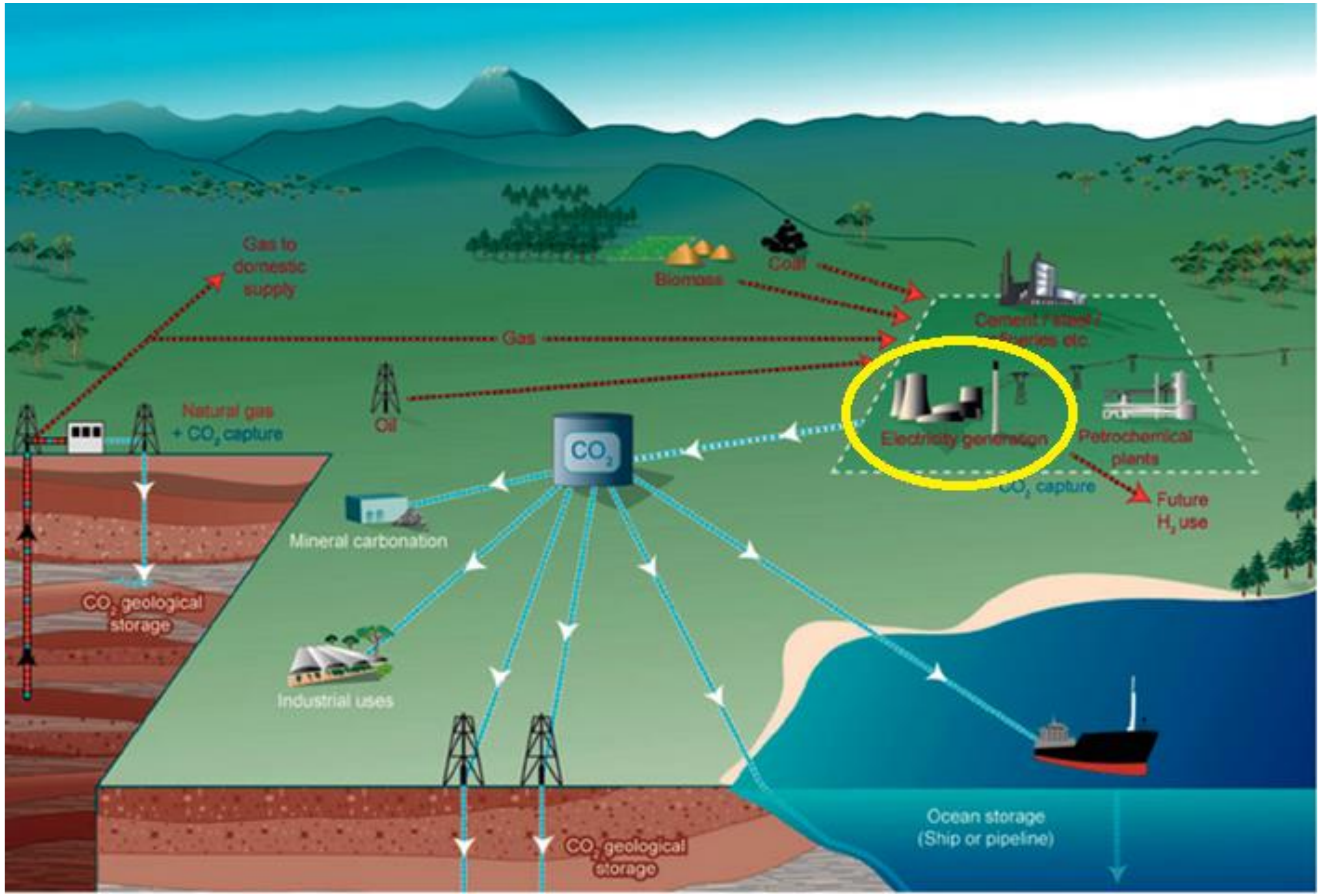


CCS systems showing the carbon sources for which CCS might be relevant, and options for the transport and storage of CO2. Source: IPCC, 2005.

NETL Baseline Studies

Thermoelectric Power with and without Carbon Capture

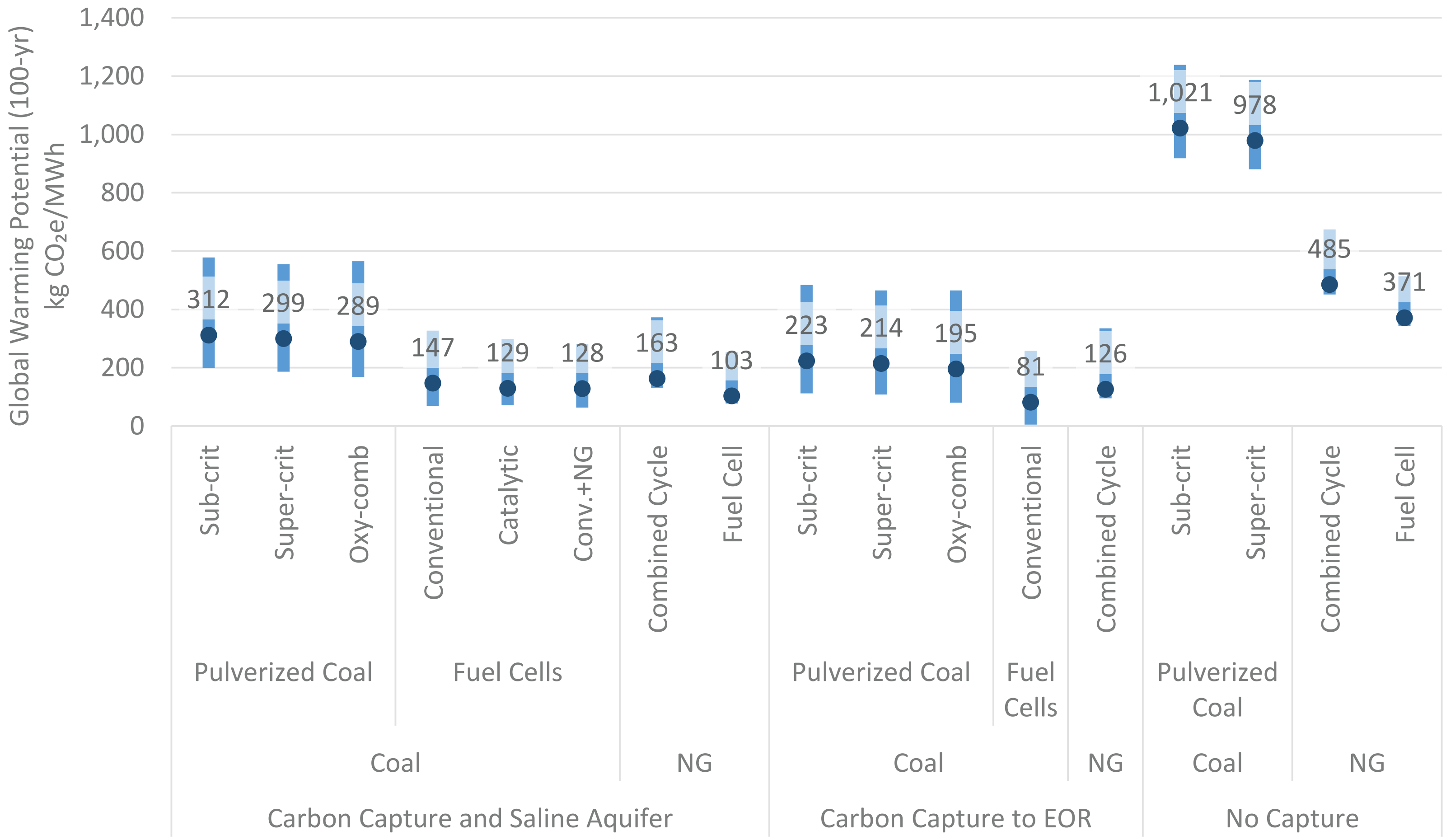
- Foundational work to provide environmental baselines to compare against alternative technologies
- Saline aquifer storage and enhanced oil recovery (EOR) were the dispositions for captured carbon dioxide



Source: IPCC, 2005.

Thermoelectric Baseline GWP – 100-yr

Plant Type, Fuel Source, and CO_2 Disposition All Affect GWP per MWh



- Benefit from sending CO_2 to EOR is the result of a displacement credit for natural dome CO_2
- All the uncertainty shown is from the rest of the life cycle – no uncertainty for power plant direct emissions

Petra Nova Plant

Located Outside of Houston, Texas

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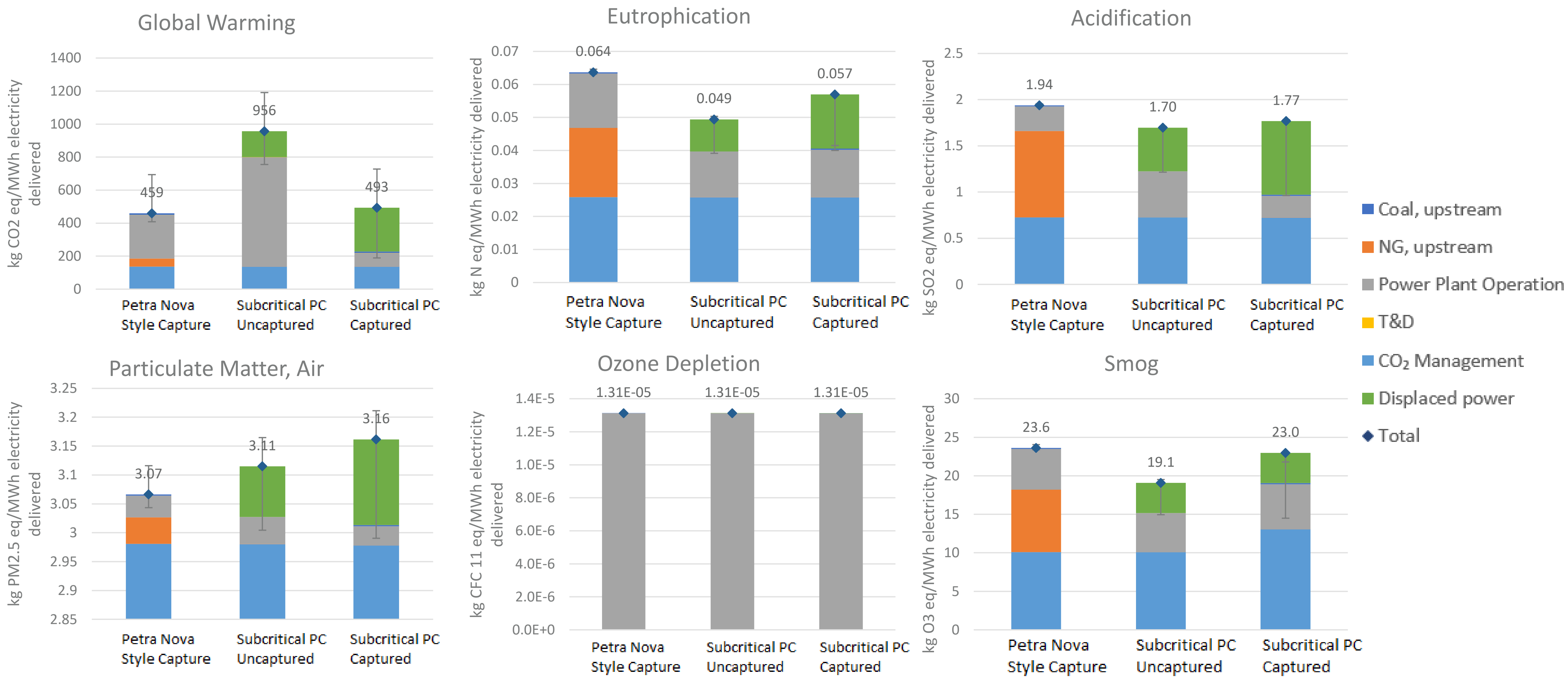
- **Partnership between JX Nippon Oil and Gas Exploration and NRG Energy**
  - US DOE grant
- **Capture unit online in 2016**
- **Petra Nova uses an amine-based capture to capture 90% of CO_2 emissions from a flue gas slipstream**
  - W.A. Parish Unit 8 (240 MW)
- **Capture unit powered by 75 MW cogeneration natural gas generator**
  - No generation from coal-fired Unit 8 used for capture unit

Source: EIA, 2017. "Petra Nova is one of two carbon capture and sequestration power plants in the world."

Petra Nova Style Capture

Petra Nova Style Capture can be an Effective Carbon Mitigation Strategy



Note: the impacts for subcritical pulverized coal are slightly different in this analysis than previous analyses as a result of improvements to our understanding of coal mine methane.

Carbon Capture for Industry

- Capture for petroleum refining and ammonia production were compared with capture for thermoelectric power

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ELSEVIER

Comparative environmental life cycle assessment of carbon capture for petroleum refining, ammonia production, and thermoelectric power generation in the United States

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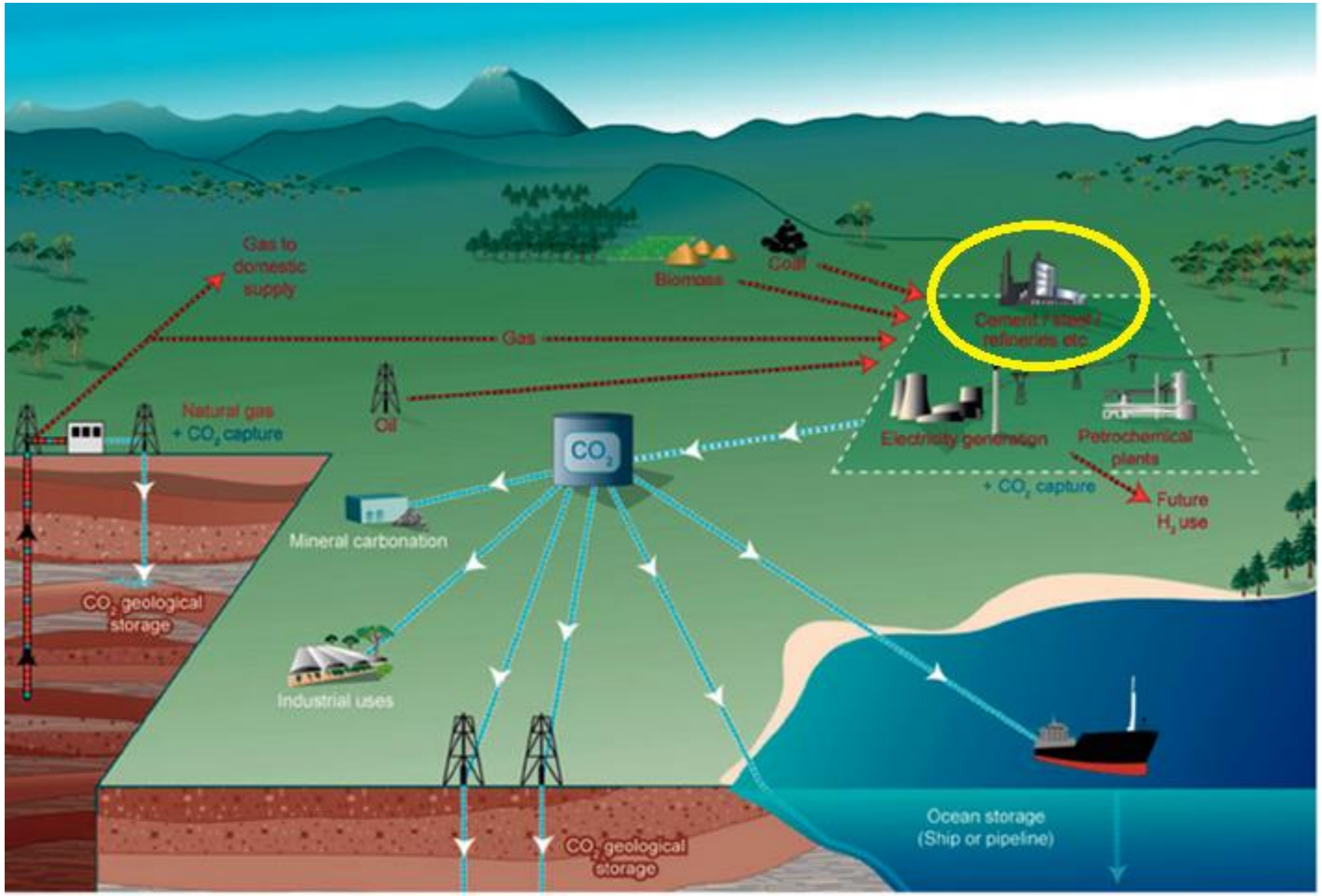
ABSTRACT

Understanding opportunities for carbon capture and storage (CCS) across sectors is important for choosing among greenhouse gas mitigation strategies. This study explores the cradle-to-gate life cycle environmental impacts of amine solvent based carbon capture systems on U.S. ammonia production, petroleum refineries, supercritical and subcritical pulverized coal power plants, and natural gas combined cycle plants. We use publicly available data to create comprehensive life cycle inventories for petroleum refining and ammonia ...

1. Introduction



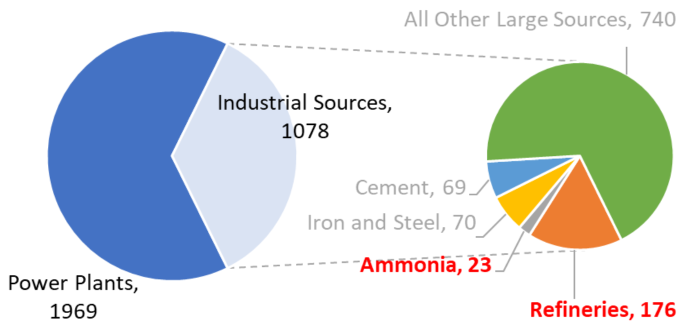
Source: IPCC, 2005.

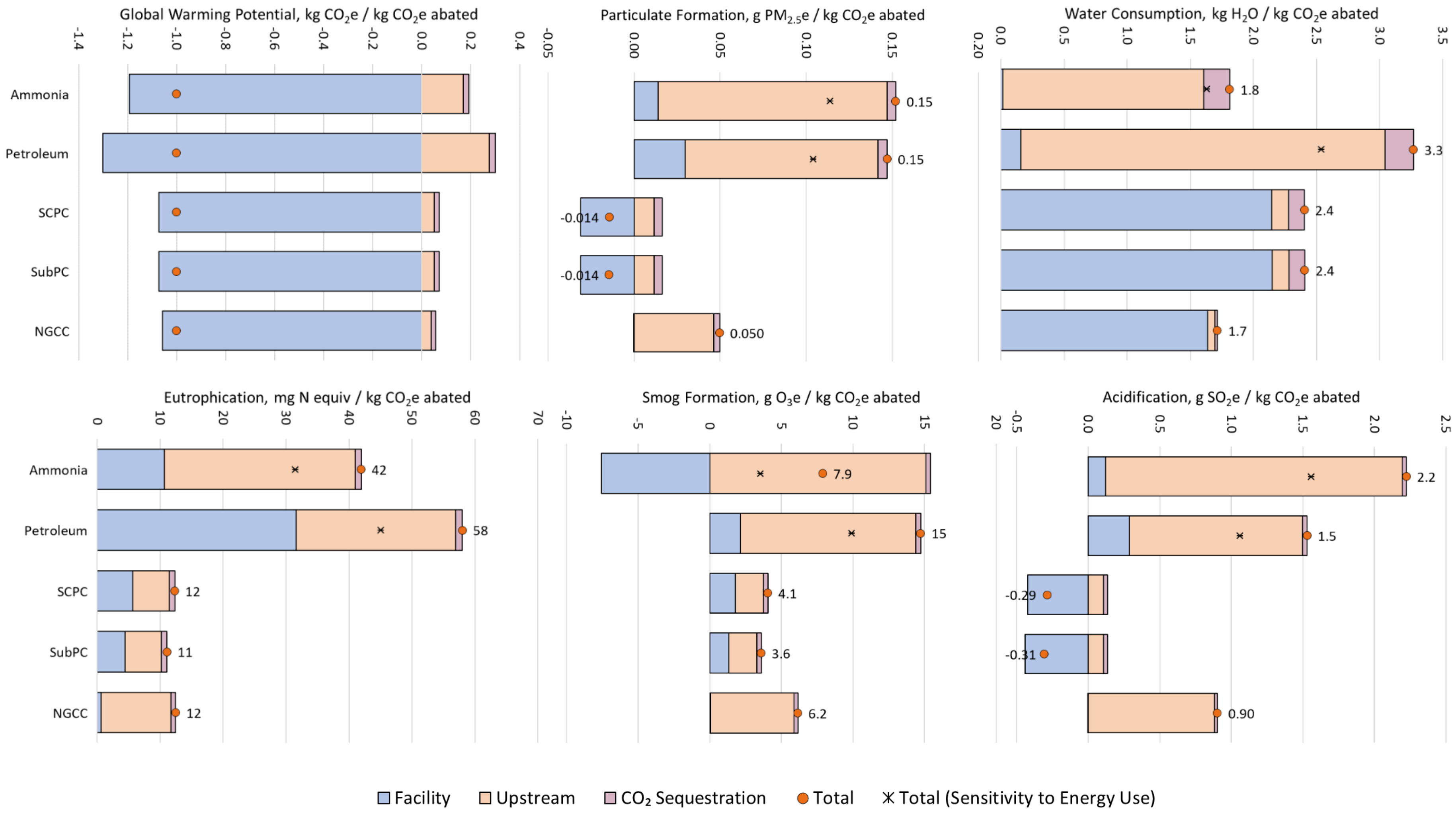
Comparative environmental life cycle assessment of carbon capture for petroleum refining, ammonia production, and thermoelectric power generation in the United States. International Journal of Greenhouse Gas Control. https://www.sciencedirect.com/science/article/pii/S175058361830817X

Comparing Industrial to Thermoelectric Capture

Capture for Thermoelectric Power has Lower Impacts per kg CO_2e Abated

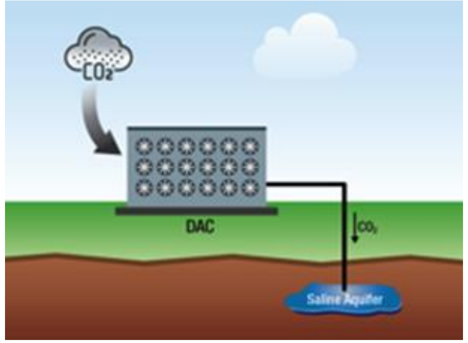
- Capture is only comparable across industries on a CO_2e abated metric
- The parasitic load for power is subject to the capture system unlike industrial systems – which leads to generally lower environmental burdens for power than petroleum refining and ammonia production

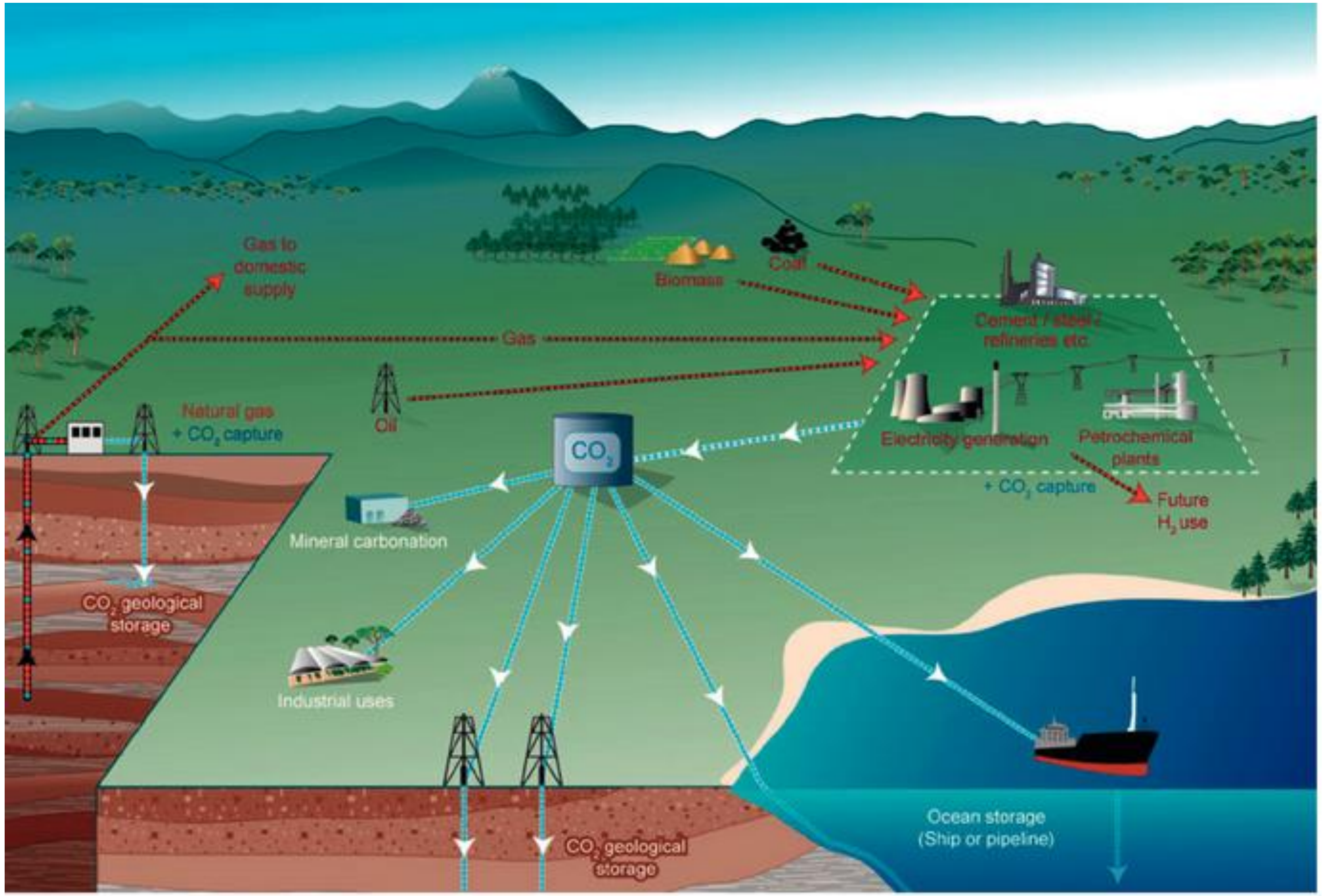




Direct Air Capture (DAC)

- New mitigation technology on the horizon - Direct Air Capture (DAC)
- We explore how DAC stacks up against other sources of CO_2 and how its end fate affects its life cycle impacts





Source: IPCC, 2005. Note: graphic pre-dates DAC IPCC inclusion.

Recent Project: Direct Air Capture Analysis

Guiding Research Questions

- 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)

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- **DAC is one of the five IPCC approaches to remove CO_2 from the atmosphere**
  - BECCS, DAC, 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

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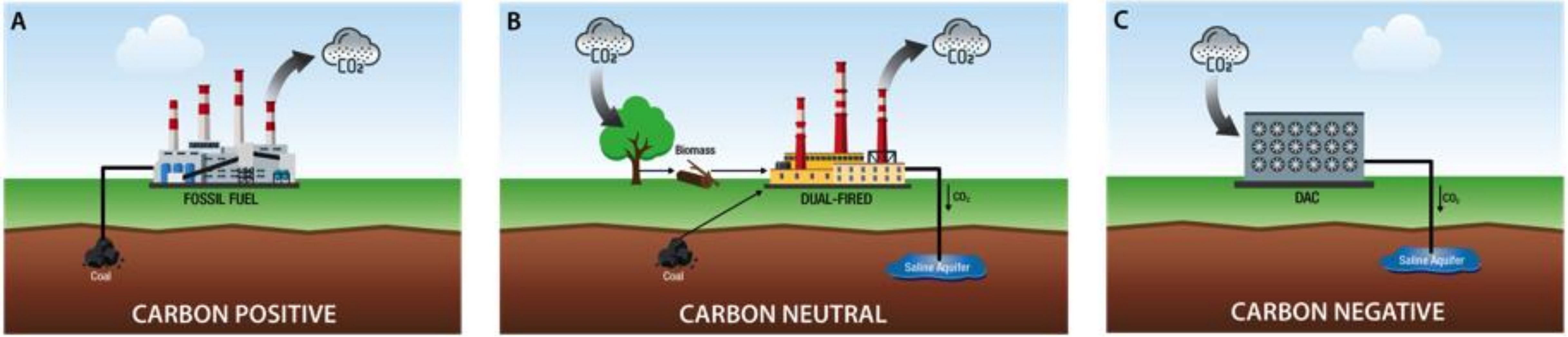
Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO2 direct air capture plants. *Journal of Cleaner Production*, *224*, 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086

Keith, D., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A Process for Capturing CO2 from the Atmosphere. *Joule*, *2*(8), 1573–1594. https://doi.org/10.1016/j.joule.2018.05.00

Is DAC Carbon Negative?

Life Cycle Carbon Equivalent Accounting Designation for GHG Mitigation

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

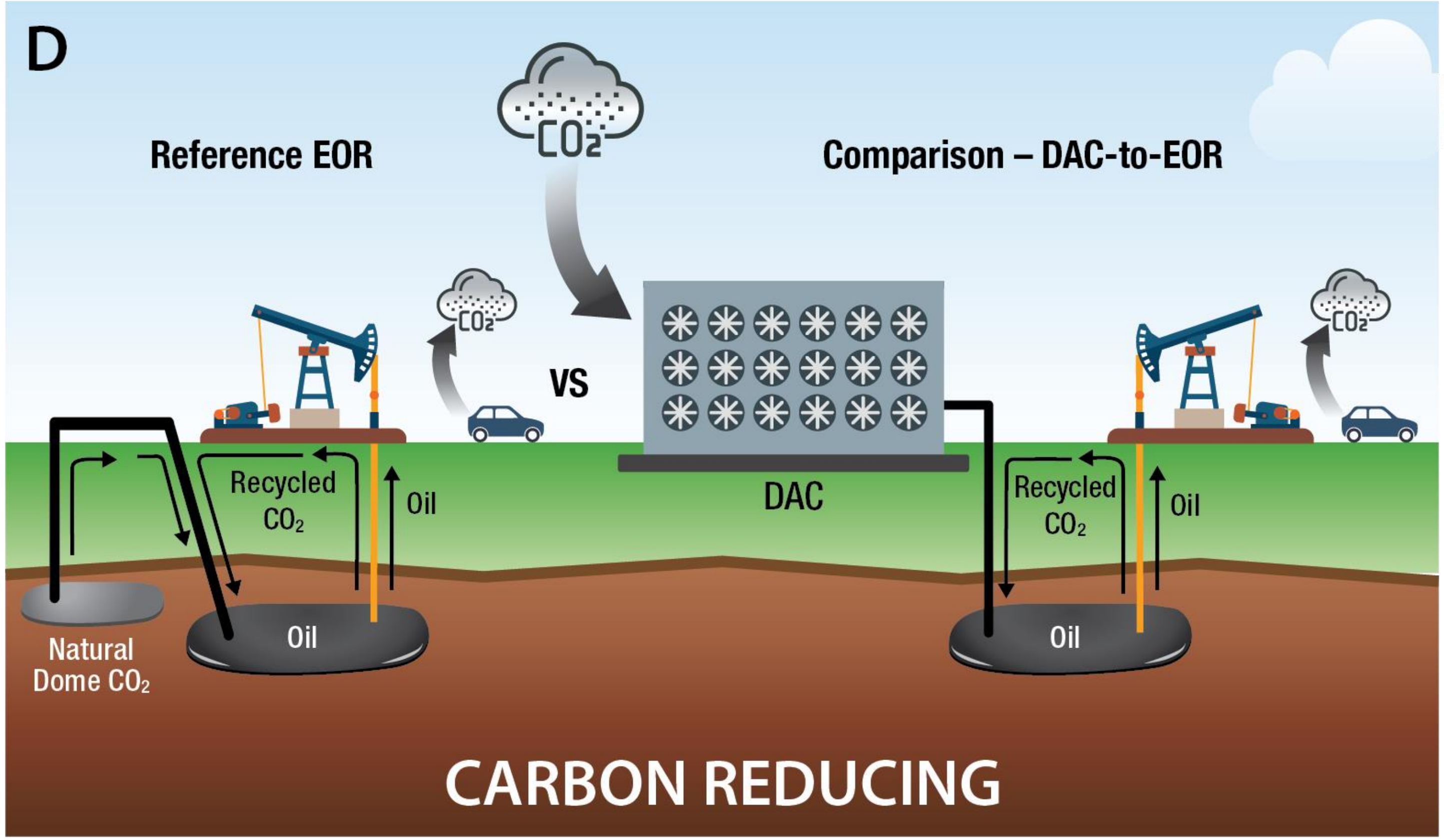


Assumed that biomass in this case is harvested sustainably

Is DAC Carbon Reducing?

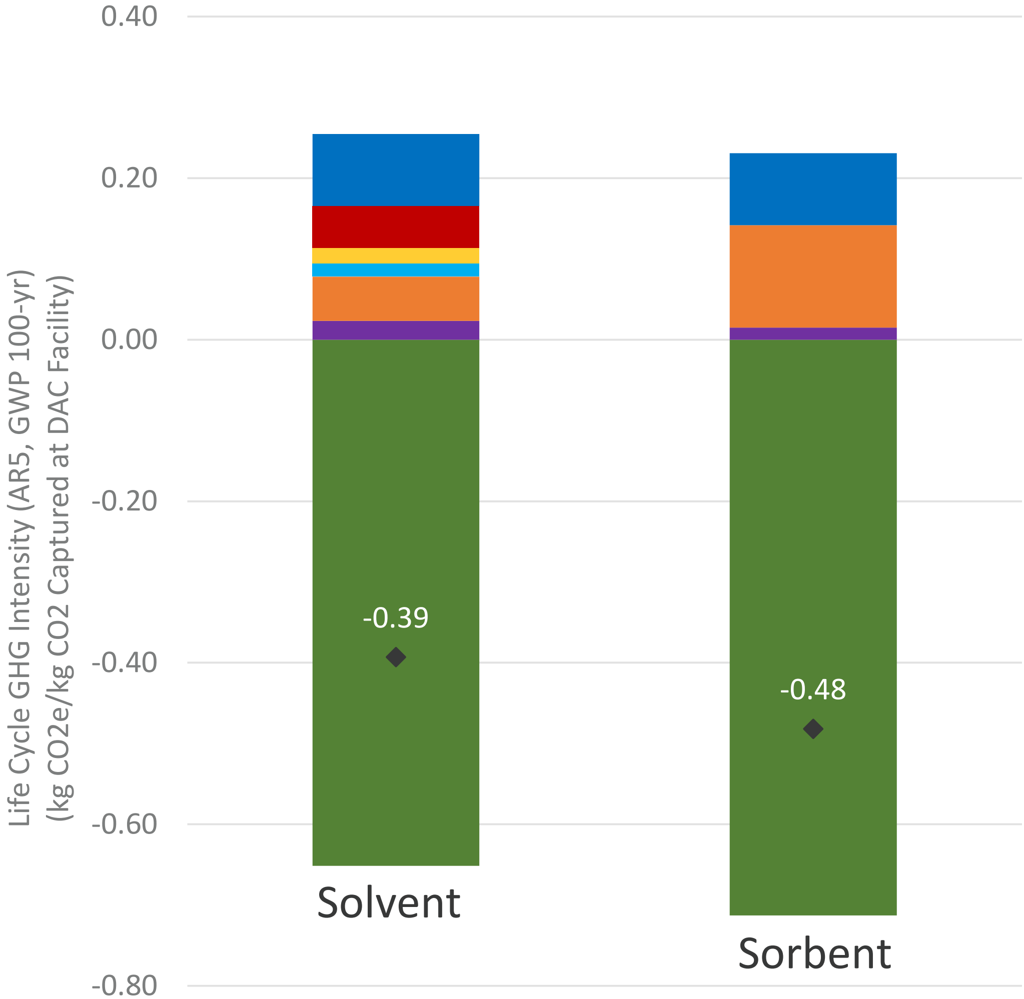
Carbon Positive Systems can be Carbon Reducing to a Comparison System

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

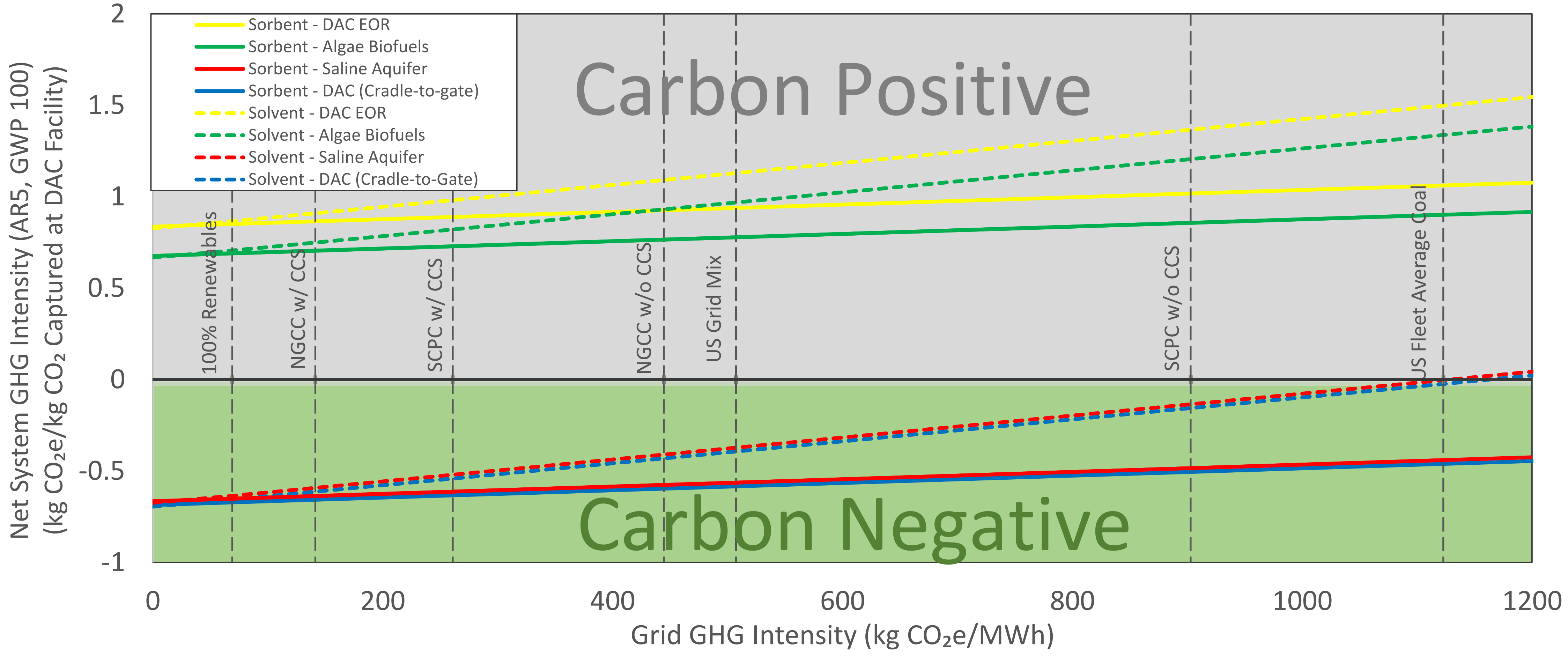
* Auxiliary loads consist of circulating water pumps, cooling tower fans, CO_2 capture and removal auxiliaries (for natural gas boiler), CO_2 compression (for natural gas boiler), feedwater pumps, ground water pumps, selective catalytic reduction (attached to the natural gas boiler for flue gas treatment),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

DAC – Net GHG Emissions

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

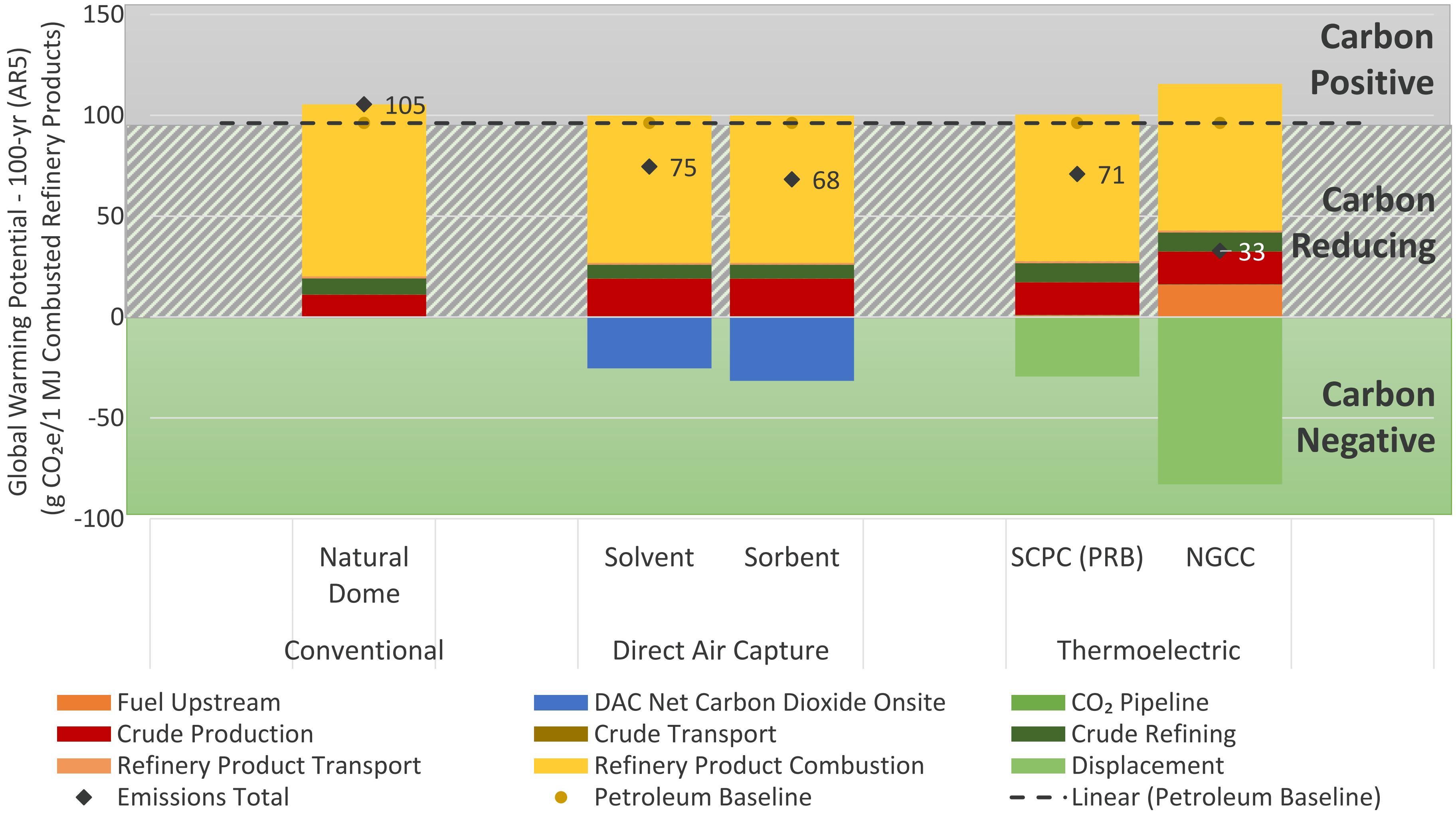


Y-axis values below zero indicate life cycle carbon negative emissions. Results that are greater than zero indicate life cycle carbon positive emissions, as these results indicate that they emit more CO_2 than is removed from the atmosphere.

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

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

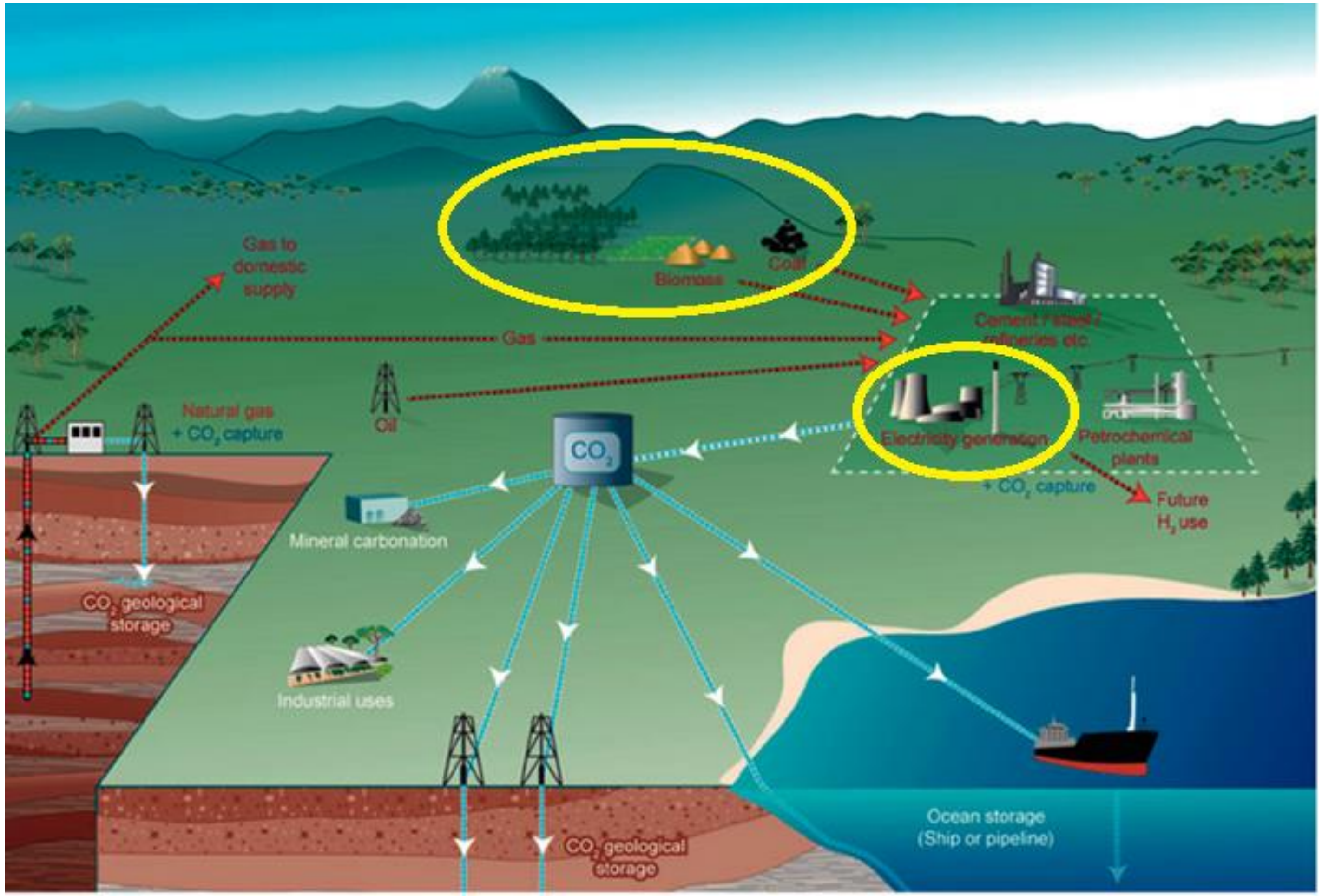
Direct Air Capture Conclusions

- **DAC-to-Saline aquifer storage removes CO_2 from the atmosphere**
  - Solvent-based DAC net emissions are -0.39kg CO2e per kg captured
  - Sorbent-based DAC net emissions are -0.48kg CO2e 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, 22%-29% lower than BAU petroleum production
  - System still produces positive emissions to the environment (no longer an IPCC negative emissions technology option)
  - Other sources of CO_2 may provide lower system emissions than DAC-to-EOR

Bioenergy with CCS (BECCS)

Co-firing Hybrid Poplar with Illinois No. 6 in a Supercritical Plant

- We explored co-firing scenarios for a 650MW power plant with and without carbon capture
- Modeled co-firing Illinois No. 6 Bituminous coal with sustainably managed Hybrid Poplar short rotation woody crop for energy production



Source: IPCC, 2005.

Bioenergy with CCS (BECCS)

Fundamental Questions

- Can you make a Coal power plant Carbon neutral using Biomass and Carbon Capture?

- If so, how much biomass do you need?

BECCS Case Descriptions

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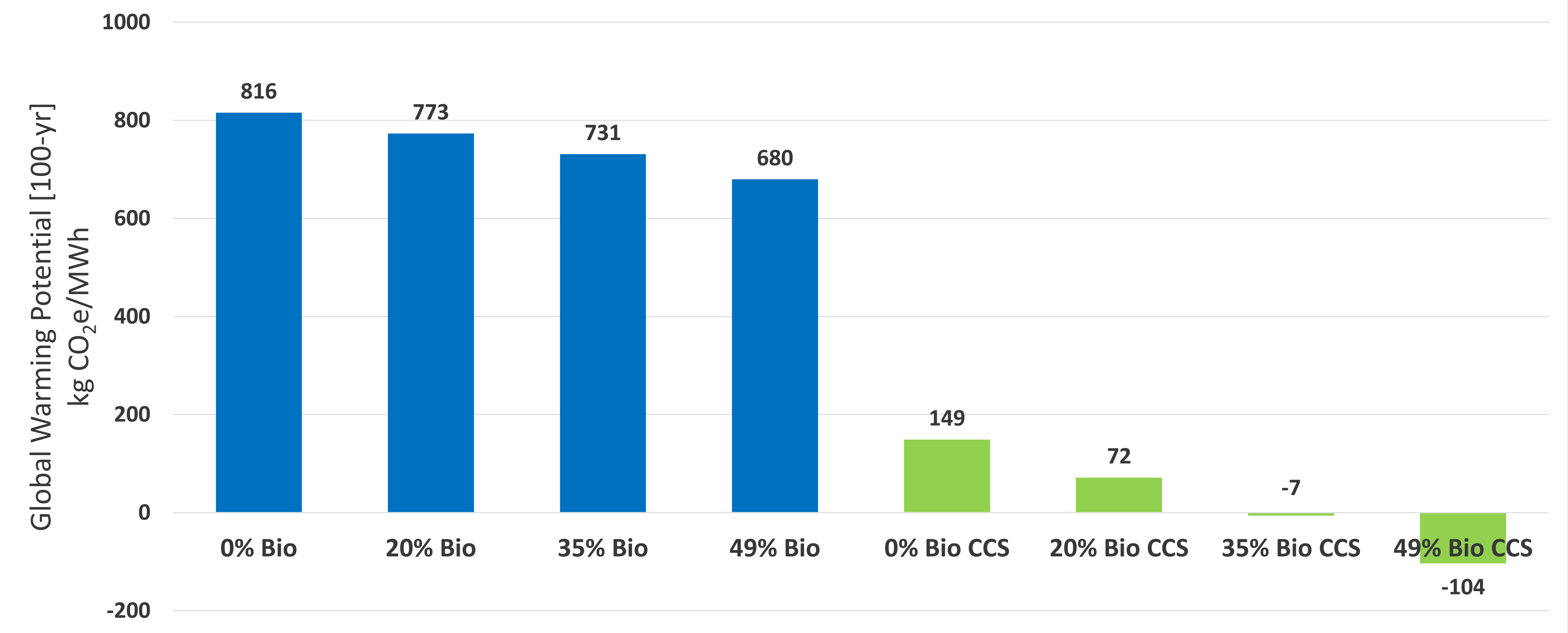
- The following case matrix was considered part of this study update
  - 20 wt%
    - Lower end of co-firing
    - Represents the majority of currently in practice co-firing rates
    - Boiler efficiency impacts not statistically significant
  - 35 wt%
    - Mid-range of feasible co-firing
    - Close to the potential net-zero greenhouse gas emissions point (with capture)
    - If the desired result is for a net-zero LCA, this co-fire rate could be changed
  - 49 wt%
    - Current potential maximum rate of co-firing based on logistical supply constraints
    - Maintains coal with biomass co-firing idea

Case	Biomass Type	Plant Type	% Biomass in Feed	CO_2 Capture %	Capture Strategy
20% Bio	Hybrid Poplar	Greenfield Supercritical	20	0	N/A
35% Bio			35		
49% Bio			49		
20% Bio CCS			20	90	Amine (Cansolv) Saline Aq. Storage
35% Bio CCS			35		
49% Bio CCS			49		

Note: The power plant in this study is a Supercritical Pulverized Coal Power Plant consistent with Revision 4 of the NETL Bituminous Baseline Study – previous power plant results in this presentation are for a Subcritical Pulverized Coal Power Plant based on Revision 3 of the NETL Bituminous Baseline Study, the GWP results are lower for the Supercritical Pulverized Coal Power Plant design due to improved plant efficiency (Subcritical versus Supercritical) and other Revision 3 to Revision 4 design improvements.

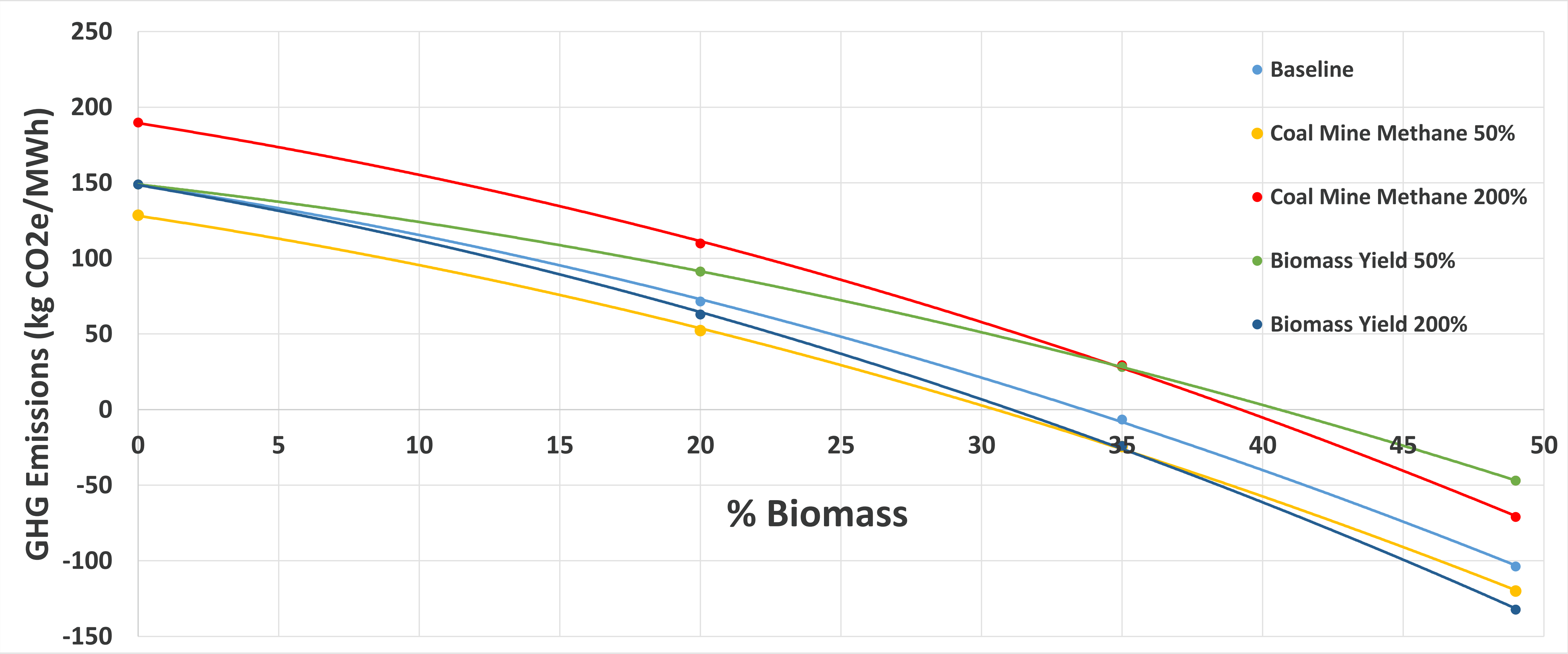
BECCS Life Cycle GWP

Carbon Neutrality is Achieved with About 35% (wt) Biomass with CCS



BECCS GHG Sensitivities

Percentage of Biomass is the Most Impactful Variable in the Model



Impact Heatmap for BECCS Scenarios

As GWP Decreases, Other Environmental Impacts Increase due to Additional Fuel Req.

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Bioenergy – Increasing biomass cofiring with and without CCS (BECCS)

Indicator	Unit	SC PC w/o Capture (B12A 0 wt%)	SC PC w/ Capture (B12B 0 wt%)	BECCS w/o Capture (PN1 20 wt%)	BECCS w/ Capture (PA1 20 wt%)	BECCS w/o Capture (PN2 35 wt%)	BECCS w/ Capture (PA2 35 wt%)	BECCS w/o Capture (PN3 49 wt%)	BECCS w/ Capture (PA3 49 wt%)
Acidification Potential	kg SO_2e	5.80E-01	3.16E-01	7.19E-01	5.24E-01	8.58E-01	7.35E-01	1.03E+00	1.00E+00
Eutrophication Potential	kg N e	1.59E-02	2.03E-02	4.72E-02	6.08E-02	7.84E-02	1.02E-01	1.17E-01	1.53E-01
Global Warming Potential [100-yr]	kg CO_2e	8.14E+02	1.47E+02	7.72E+02	6.93E+01	7.30E+02	-8.83E+00	6.78E+02	-1.06E+02
Ozone Depletion Potential	kg CFC-11e	4.46E-09	5.71E-09	2.10E-08	2.71E-08	3.78E-08	4.93E-08	5.89E-08	7.75E-08
Particulate Matter Formation Potential	kg PM2.5e	1.15E-01	1.23E-01	1.20E-01	1.31E-01	1.24E-01	1.40E-01	1.29E-01	1.50E-01
Photochemical Smog Formation Potential-	kg O_3e	8.74E+00	9.96E+00	1.08E+01	1.27E+01	1.29E+01	1.55E+01	1.56E+01	1.90E+01
Water Consumption	kg	2.86E+02	3.66E+02	6.03E+03	7.76E+03	1.17E+04	1.52E+04	1.87E+04	2.45E+04

How to Access NETL Related LCA Products

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www.netl.doe.gov/LCA

- **Conference Presentations**
  - Life Cycle Greenhouse Gas Analysis of Direct Air Capture Systems. ACLCA 2020.
  - TEA & LCA of Biomass Co-Fire with Carbon Capture and Sequestration. ACLCA 2020.
  - LCA of Carbon Capture Retrofit Using the “Petra Nova Style” Model. ACLCA 2018. https://www.osti.gov/biblio/1576780
  - Life Cycle Analysis of Carbon Capture Retrofit Using the Petra Nova Model. AIChE 2018. https://www.osti.gov/biblio/1592449
  - Impacts of Carbon Capture on Life Cycle Inventory of Ammonia and Petroleum Products for Comparison with Thermoelectric Power Generation. ACLCA 2017. https://www.osti.gov/biblio/1433631
- **Journal Articles**
  - *Comparative environmental life cycle assessment of carbon capture for petroleum refining, ammonia production, and thermoelectric power generation in the United States*. International Journal of Greenhouse Gas Control. https://www.sciencedirect.com/science/article/pii/S175058361830817X
  - Life Cycle Greenhouse Gas Emissions Analysis of Direct Air Capture of Carbon Dioxide Using Solvent and Sorbent Technologies (in review)
  - Technoeconomic and Life Cycle Analysis of Bio-Energy with Carbon Capture and Storage (BECCS) Analysis (in development)
- **Reports**
  - Life Cycle analysis of Carbon Capture Retrofit Using the Petra Nova Model (in review)
  - Technoeconomic and Life Cycle Analysis of Bio-Energy with Carbon Capture and Storage (BECCS) Baseline (in review)
  - Life Cycle Analysis: Sub-Critical Pulverized Coal (SubPC) Power Plants https://netl.doe.gov/energy-analysis/details?id=6e3df24b-5f46-4d35-9d98-73ea955833d8
  - Life Cycle Analysis: Supercritical Pulverized Coal (SCPC) Power Plant https://netl.doe.gov/energy-analysis/details?id=d54ec6d5-1595-4352-b646-e748c3bf8b09
  - Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plants https://netl.doe.gov/energy-analysis/details?id=81822318-145b-445a-98db-79427bb699eb
  - Life Cycle Analysis: Solid Oxide Fuel Cell (SOFC) Power Plants https://netl.doe.gov/energy-analysis/details?id=ce10d08f-d0b0-4273-9998-af9cc2da6157
  - Life Cycle Analysis: Oxy-combustion Supercritical Pulverized Coal (OxyPC) Power Plants https://netl.doe.gov/energy-analysis/details?id=b9409f8d-0ea9-4eea-a3cf-a92bc123eb40

Discussion and Conclusions

- **LCA can be used to answer complex questions and guide both R&D as well as policy**
- **Carbon capture is an effective technology to lower the greenhouse gas impact of thermoelectric power**
  - There are environmental tradeoffs associated with capture due to increased power demand
- **Petra Nova style capture (stand alone energy resource for electricity and heat to operate the captures system) is equally environmentally competitive as integrated carbon capture solution**
- **Industrial capture presents near term opportunities for decarbonization – unique challenges need to be addressed to implement for various carbon sources and concentrations**
  - Industrial sources present key opportunities for carbon capture cost reduction and industrial decarbonization
- **BECCS requires about 30% biomass co-firing by weight to achieve carbon neutrality**
  - Carbon capture provides a larger reduction in GHGs than co-firing with biomass, but biomass is also required to achieve carbon neutrality or carbon negative emissions
- **DAC with saline aquifer storage is one of the potential negative emissions technologies presented by the IPCC**
  - DAC-to-EOR can be environmentally beneficial to BAU cases, but capture for thermoelectric power provides a larger GHG reduction in the short-term

Contact Information

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LCA Life Cycle Analysis
energy sustainability

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Backup Slides

Life Cycle Impact Assessment

Converts emissions to environmental impact equivalences (i.e., mid-point impacts).

Global | Air | Local | Water

- **Global Warming Potential (GWP):** is the heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of carbon dioxide (CO_2). GWP is dependent on the time horizon the greenhouse gas emission impacts are assessed; 20 and 100-year time frames are commonly reported, with 100-year being default time horizon. GWP values are defined by the Intergovernmental Panel on Climate Change (IPCC). IPCC 5th Assessment Report values applied in this study on a 20 and 100-year basis are:
  - Carbon Dioxide (CO2): 20-year: 1; 100-year: 1.
  - Methane (fossil) (CH4): 20-year: 87; 100-year: 36.
  - Nitrous oxide (N_2O): 20-year: 268; 100-year: 298.
  - Sulfur Hexafluoride (SF_6): 20-year: 17,500; 100-year: 23,500.
- **Acidification Potential:** is the increased concentration of hydrogen ions in a local environment. Substances, which cause acidification, can cause damage to building materials, paints, and other human-built structures, lakes, streams, rivers, and various plants and animals.
- **Eutrophication Potential:** is the enrichment of an aquatic ecosystem with nutrients (nitrogen, phosphorus) that accelerate biological productivity (growth of algae and weeds) and an undesirable accumulation of algal biomass. High levels of nitrogen and phosphorous can cause adverse effects on local water ways and other downstream destinations.
- **Ozone Depletion Potential:** is the deterioration of ozone within the stratosphere by chemicals such as chlorofluorocarbons (CFCs). Stratospheric ozone provides protection for people, crops, and other plant life from radiation.
- **Particulate Matter Formation Potential:** is the increased concentration of a mixture of solid particles and liquid droplets found in the air" that are smaller than 10 microns in diameter that have the potential to cause human respiratory effects.
- **Photochemical Smog Formation Potential:** is created by various chemical reactions, which occur between nitrogen oxides (NOx) and volatile organic compounds (VOCs) in sunlight. Ground level ozone can have both ecological impacts on crops and ecosystems as well as cause respiratory effects in humans.
- **Water Consumption:** volume of water consumed across the life cycle of the product or service. Increased water consumption in water scarce areas may restrict water availability for human, agricultural, and other uses.

LCIA methods for non-GWP indicators is based on the U.S. EPA "Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI)" Bare, 2008; Bare 2011

Energy Consumption for DAC Systems

NATIONAL ENERGY TECHNOLOGY LABORATORY

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)

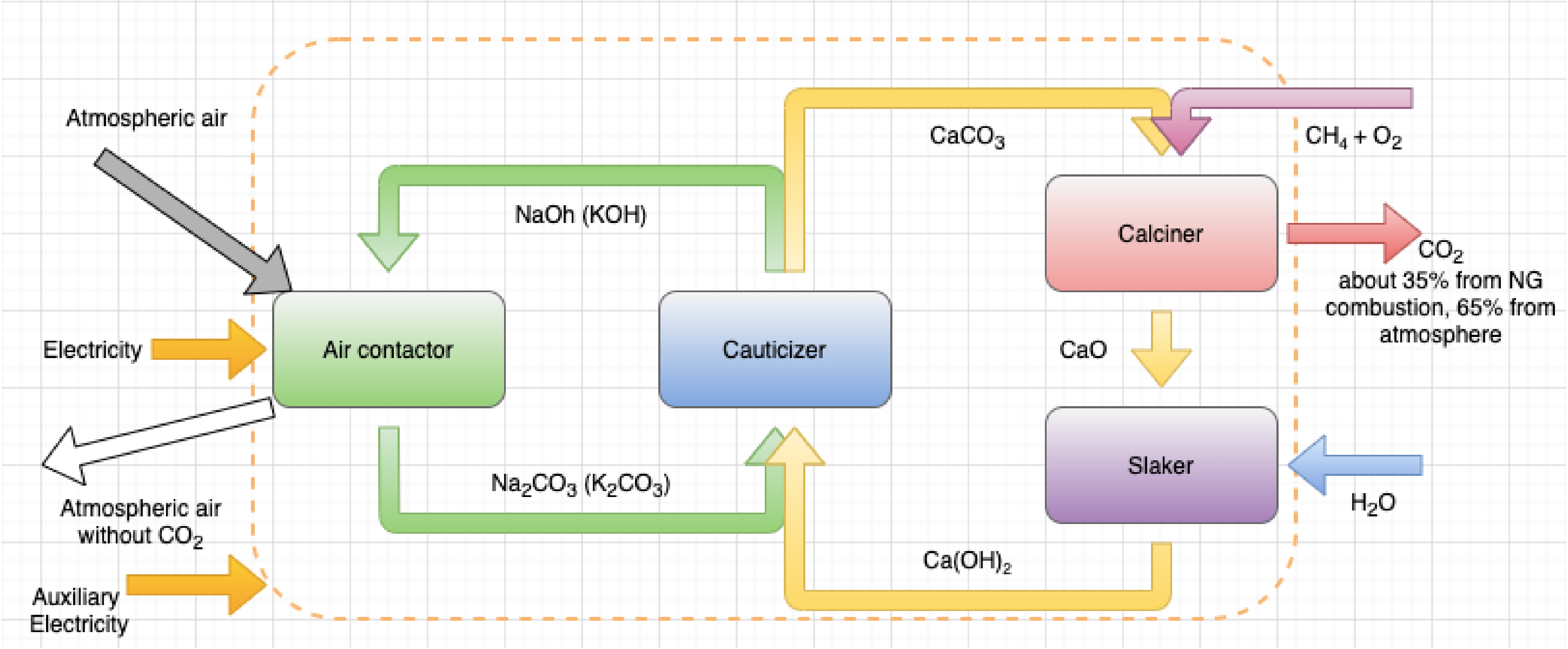
Sandalow, D., Friedmann, J., McCormick, C., & McCoy, S. (2018). *Direct Air Capture of Carbon Dioxide* (pp. 1–39). Innovation for Cool Earth Forum. https://www.icef-forum.org/pdf2018/roadmap/ICEF2018_DAC_Roadmap_20181210.pdf

Ishimoto, Y., Sugiyama, M., Kato, E., Moriyama, R., Tsuzuki, K., & Kurosawa, A. (2017). *Putting Costs of Direct Air Capture in Context* (SSRN Scholarly Paper ID 2982422). Social Science Research Network. https://doi.org/10.2139/ssrn.2982422

Keith, D., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A Process for Capturing CO2 from the Atmosphere. *Joule*, 2(8), 1573–1594. https://doi.org/10.1016/j.joule.2018.05.006

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

Solvent-Based DAC Flow Diagram



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

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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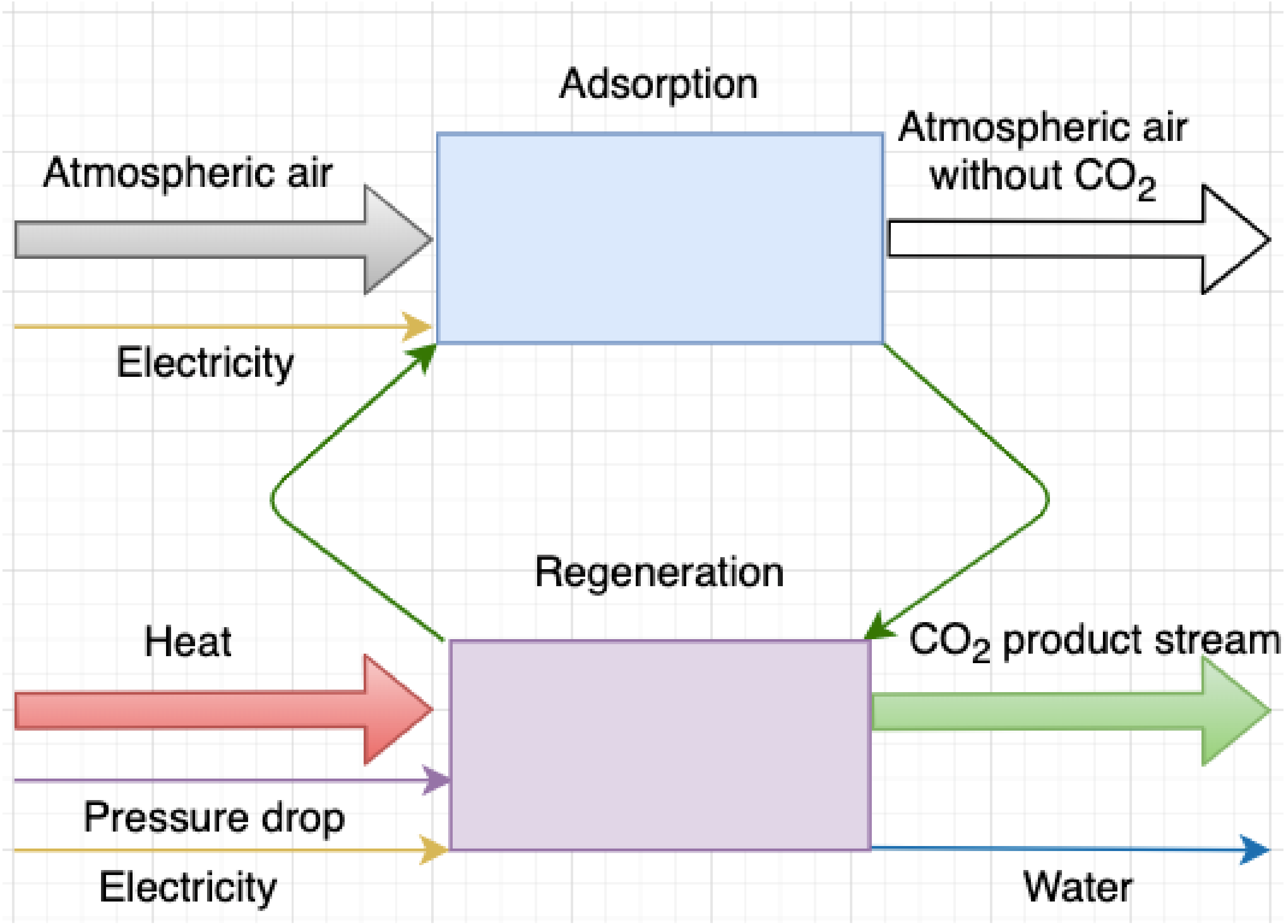
Sorbent-Based DAC Flow Diagram

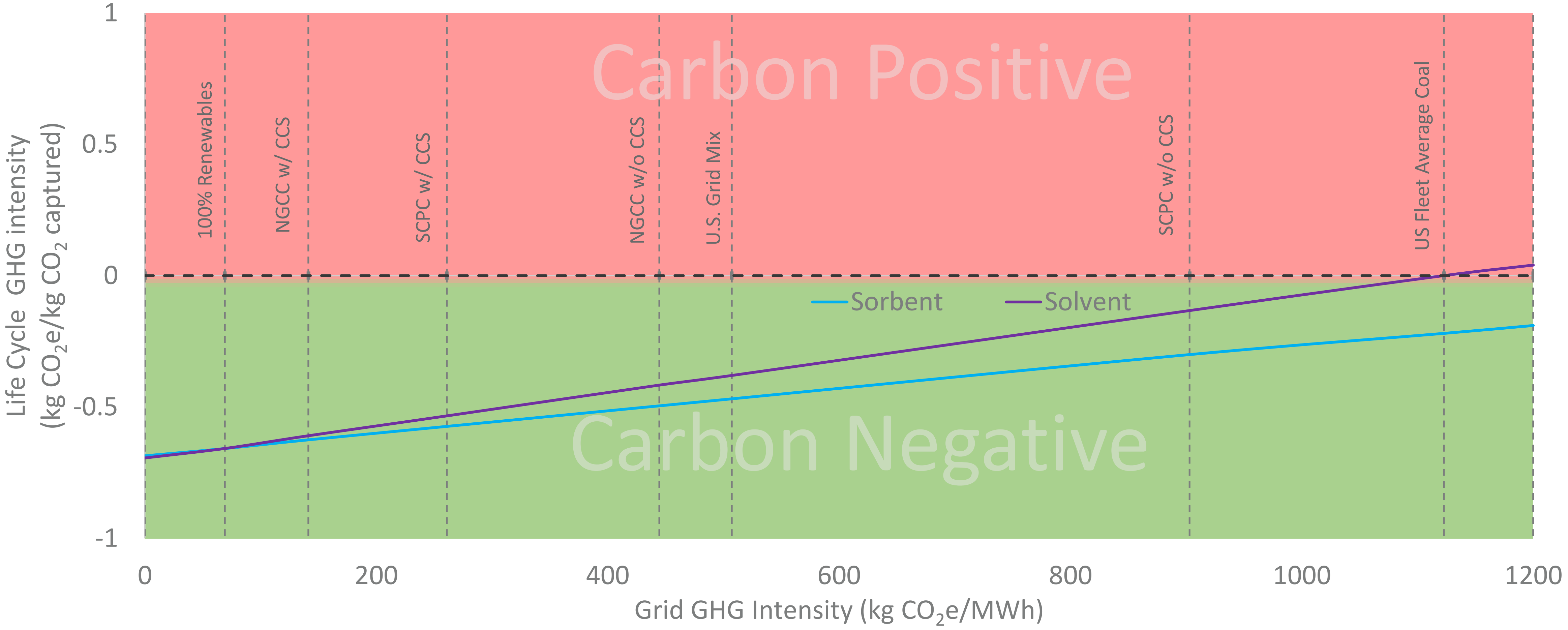


Sorbent DAC System Flow Diagram (Fasihi et al., 2019)

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

Solvent vs. Sorbent - Net CO_2 Emissions

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.

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

Sorbent-Based DAC – Net GHG Emissions

Cradle-to-Grave impacts with saline aquifer storage

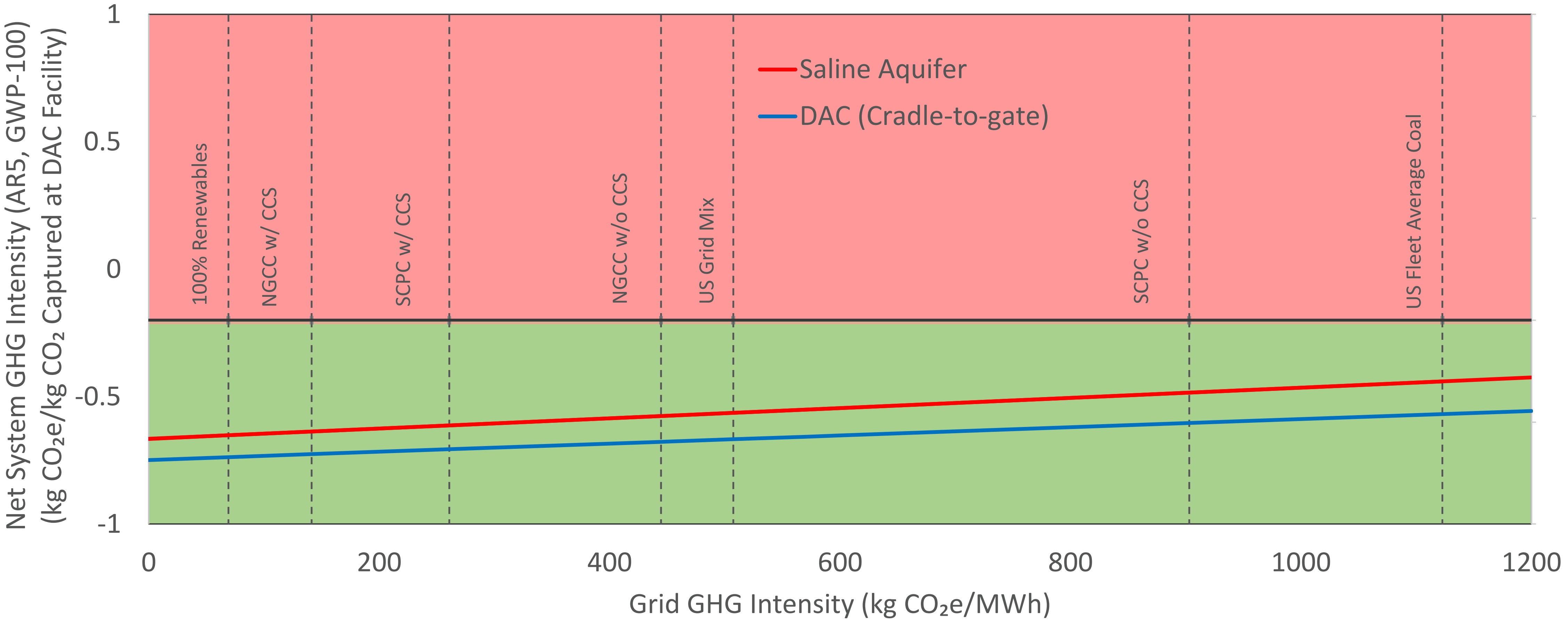


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Table 2
LT solid sorbent DAC specifications.

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	1199-2461$_{el,th}$ [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.