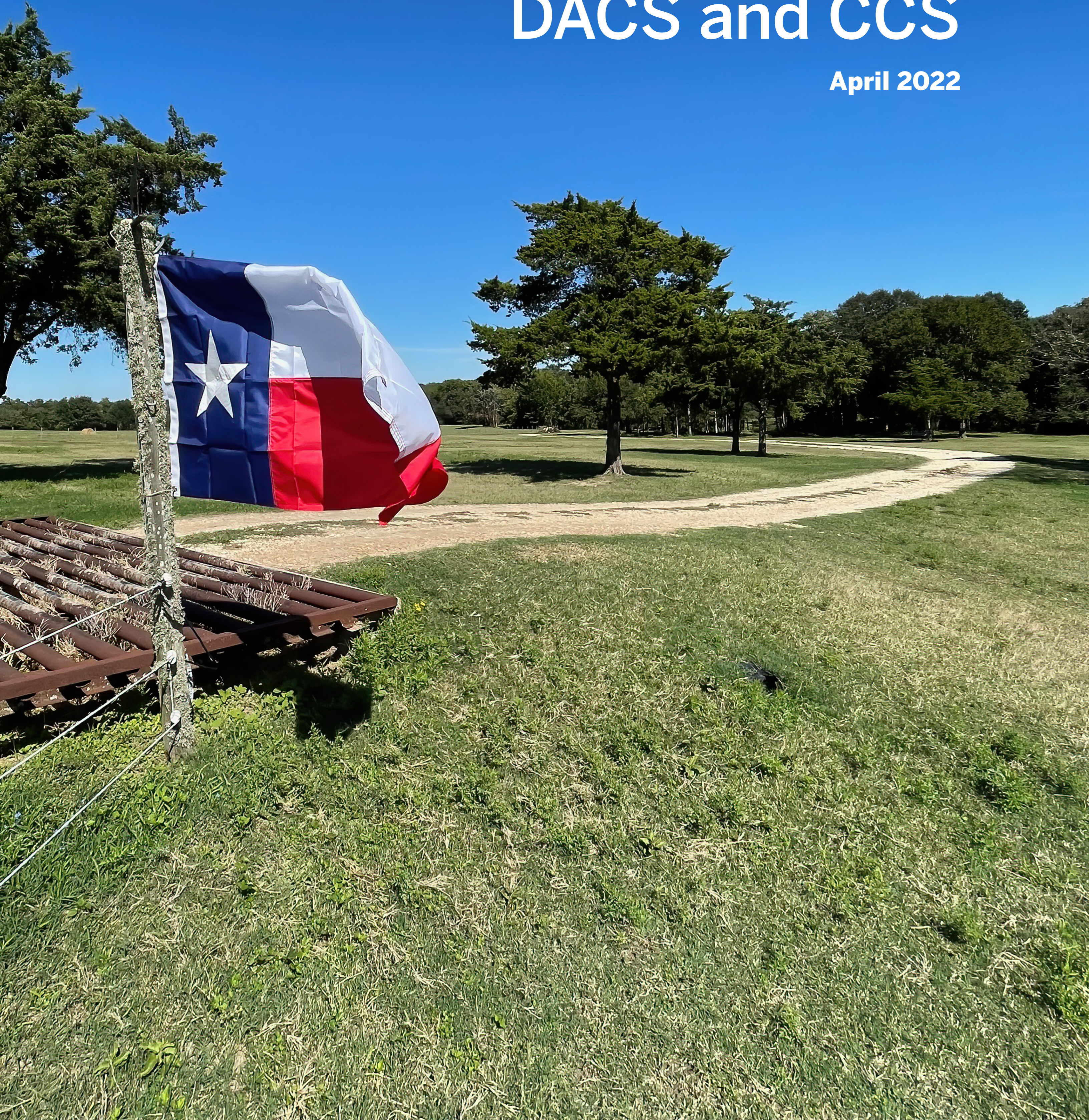
Don't Mess with Texas

Getting the Lone Star State to Net-Zero by 2050

Appendix A
DACS and CCS

April 2022



Appendix A: DACS and CCS

Table A1: Carbon Dioxide Emissions Captured Through Power Sector CCS and DACS (MMT)

	Electrification		Electrification: Accelerated Clean Power		Hydrogen and Carriers		Extensive Capture	
	CCS	DACS	CCS	DACS	CCS	DACS	CCS	DACS
2018	0	0	0	0	0	0	0	0
2020	0	0	0	0	0	0	0	0
2025	8.4E–05	0	9.6E–05	0	2.8E+01	3	9.0E–05	0
2030	3.1E+00	100	3.1E+00	100	2.5E+01	60	3.2E+00	150
2035	1.9E+00	180	2.2E–05	160	1.0E+01	130	1.8E+00	300
2040	1.6E+00	260	2.2E–05	240	9.3E+00	170	1.4E+00	490
2045	1.8E–04	310	3.4E–05	300	1.3E–04	210	1.3E–04	690
2050	1.5E–04	360	3.6E–05	340	2.3E–05	220	1.3E–04	900

Table A2: DACS and Other Carbon Removal Technology Potentials in 2050

2050 Carbon Removal Capacity, All Technologies (MMT)	2050 DACS Capacity Estimates (MMT)	Region	Scenario	Source	Other Non-DACS Carbon Removal Technologies Included in Analysis
900	900	Texas	Extensive Capture	Our Analysis	N/A
360	360	Texas	Electrification		
340	340	Texas	Electrification: Accelerated Clean Power		
220	220	Texas	Hydrogen and Carriers		
0	0	Texas	BAU		
602	269	Texas	Slow Demand	Decarb America[1]	Natural Gas Reformation for production of Blue Hydrogen, Technologies that can capture CO2 from the exhaust of large point sources
426	247	Texas	Low Biomass		
192	157	Texas	No Fossil		
680	153	Texas	Constrained Renewables + Slow Demand Transformation		
313	139	Texas	High Renewables, High Electrification		
252	107	Texas	High Conservation		
311	46	Texas	Constrained Renewables		
0.8	0	Texas	Reference		
1,758	723	U.S.	Less High Electrification	Net-zero America[2]	Natural Gas Hydrogen/ Electricity, BECCS Electricity/Hydrogen/ Pyrolysis, Cement via 90% post-combustion capture
687	127	U.S.	100% Renewable		
1,670	8.7	U.S.	Renewable Constrained		
1,677	0.097	U.S.	High Biomass		
1,060	0.081	U.S.	High Electrification		
1,936	633	Global	NZE	IEA[3]	BECCS
3,500		Global	IPCC*		
16,000		Global	IPCC*		
24,600**	5,000**	Global	High Estimate**	Fuss et al[4]	BECCS, Afforestation and Reforestation, Enhanced Weathering, Ocean Fertilization, Biochar, Soil Carbon Sequestration
6,000**	500**	Global	Low Estimate**		

*Represents low and high range of five different scenarios from the IPCC, as cited in IEA

**Estimated sustainable potentials based on systematic literature review, entries represent low and high end of technology ranges

Table A2: DACS Cost Comparison *all costs listed as reported in source*

Listed Technology	Listed Fuel Sources	Capacity (t/yr)	Reported Capital Costs (2020$/t/yr)	Electric demand (kWh/t)	Heat/fuel demand (GJ/t)	Levelized Cost of Capture (2020$/ t-$CO_2$)	Notes	Source
HT-aqueous solution	Natural Gas & Electricity	–	694	366	5.3	113–163	Low Estimate; range is initial to floor cost, with average capital recovery factor either 7.5% or 12.5%	Keith et al (2018)[5]
HT-aqueous solution	Natural Gas	–	1,146	0	8.8	168–232	High Estimate; range is with average capital recovery factor as 7.5% or 12.5%	Keith et al (2018)[5]
LT-solid sorbent	Natural Gas & Electricity	–	812–2170	286–444	3.4–4.8	~145–445 (2025) ~60–180 (2075)	process utilizes waste heat, range in capital costs is initial to floor, ranges in LCOR based on electricity source	NAS[6], via Hanna et al (2021)'[7]
HT-aqueous solution	Natural Gas & Electricity	–	772–1334	350–594	5.3–12.2	~215–500 (2025) ~140–300 (2075)	range in capital costs is initial to floor, ranges in LCOR based on electricity source	NAS[6], via Hanna et al (2021)'[7]
HT-aqueous solution	Electricity	–	592–769	3322–4358	0	~225–1,100+ (2025) ~155–440 (2075)	ranges in LCOR based on electricity source	NAS[6], via Hanna et al (2021)'[7]
HT-aqueous solution	Electricity	1,000,000	815	1535	0	186	fully electric, DACS systems costs (CAPEX, variable, etc) used in the present report based on this example	Fasihi et al (2019)[8]
HT-aqueous solution	Natural Gas & Electricity	1,000,000	1583	494	8.1	309	listed as optimistic, heat demand converted from 2250 (kWh-th/t)	Socolow et al (2011)[9] via Fasihi et al (2019)[8]
HT-aqueous solution	Natural Gas & Electricity	1,000,000	2086	494	8.1	395	listed as pessimistic, heat demand converted from 2250 (kWh-th/t)	Socolow et al (2011)[9] via Fasihi et al (2019)[8]

Listed Technology	Listed Fuel Sources	Capacity (t/yr)	Reported Capital Costs (2020$/t/yr)	Electric demand (kWh/t)	Heat/fuel demand (GJ/t)	Levelized Cost of Capture (2020$/t-$CO_2$)	Notes	Source
HT-aqueous solution	Natural Gas & Electricity	1,000,000	1032	0	8.8	151, 209	heat demand converted from 2450 (kWh-th/t), separate LCOR values based on WACC of 5.6% and 11.7%	Keith et al (2018)[5]
HT-aqueous solution	Natural Gas & Carbon-free electricity	1,000,000	714	0	8.8	114, 153	Nth plant, heat demand converted from 2450 (kWh-th/t) , separate LCOR values based on WACC of 5.6% and 11.7%	Carbon Engineering via Fasihi et al (2019)[8]
HT-aqueous solution	Natural Gas & Carbon-free electricity	1,000,000	625	366	5.3	110–112, 137–147	Nth plant, heat demand converted from 1460 (kWh-th/t) , separate LCOR values based on WACC of 5.6% and 11.7% and ranges based on price of electricity	Carbon Engineering via Fasihi et al (2019)[8]
HT-aqueous solution	Natural Gas & Carbon-free electricity	1,000,000	549	77	5.3	85–87, 115–117	Nth plant, heat demand converted from 1460 (kWh-th/t), separate LCOR values based on WACC of 5.6% and 11.7% and ranges based on price of electricity	Carbon Engineering via Fasihi et al (2019)[8]
LT-solid sorbent	Electricity and Free Waste Heat	360,000	730	250	6.3	155, 120	range is initial to floor cost; cost based on free waste heat, heat demand converted from 1750 (kWh-th/t)	Fasihi et al (2019)[8]
LT-solid sorbent	Electricity and Free Waste Heat	3600	1220	694	7.5	224, 203	cost based on free waste heat, heat demand converted from 2083 (kWh-th/t)	Roestenberg (2015) via Fasihi et al (2019)[8]
LT-solid sorbent	Electricity and Free Waste Heat	360,000	730	694	7.5	177, 135	cost based on free waste heat, heat demand converted from 2083 (kWh-th/t)	Roestenberg (2015) via Fasihi (2019)[8]
HT-aqueous solution	Natural Gas & Carbon-free electricity	76,000	–	161	17 – 40	<140***	Costs presented in 2011$	Keith et al 2006[10]
HT-aqueous solution	Natural Gas & Electricity	1,000,000	2200	490	8.1	~600*	Costs presented in 2011$	Socolow et al (2011)[9] via Fuss et al (2018)[4]

Listed Technology	Listed Fuel Sources	Capacity (t/yr)	Reported Capital Costs (2020$/t/yr)	Electric demand (kWh/t)	Heat/fuel demand (GJ/t)	Levelized Cost of Capture (2020$/ t-$CO_2$)	Notes	Source
Theoretical Thermodynamic Limit	Natural Gas & Electricity	–	–	–	–	~1000	Theoretical model based on thermodynamic limits, costs presented in 2011$	House et al (2011)[11]
HT-aqueous solution	Electricity	400	–	–	–	<500	Costs presented in 2011$	Simon et al (2011)[12]
HT-aqueous solution	Natural Gas & Electricity	1,000,000	–		–	~300	Costs presented in 2011$	Zeman (2014)[13]
LT-solid sorbent	Natural Gas & Electricity	–	–	–	2.6	60–190	Temperature and vacuum swing adsorption process, 2.6GJ/tonne total enegy requirement (sources undistinguished), costs presented in 2011$	Sinha et al (2017)[14]
LT-solid sorbent	Natural Gas & Electricity	–	–	–	–	600	Costs presented in 2011$	Climeworks via Fuss et al (2018)[4]

LT-Solid Sorbent: Ambient air passes through a solid filter (Often with help from fans), CO_2 chemically binds to the filter, and CO_2 depleted air leaves the system. Then, the system is closed off, air is removed, and the system is heated to about 100 deg C (varies by technology) to release the CO_2. Released CO_2 is collected and transported out of the system. The system requires electricity to run fans and control systems, and the heat can be provided by low-grade or waste–heat.

HT-Aqueous: Ambient air passes through a sprayed or flowing solution which absorbs CO_2. The solution, now containing CO_2, must then be processed and heated to a high temperature to release CO_2 for capture. The solvent can then be reused. Electricity is required to blow air through the system and to move the solution from one unit to another. The heat can be provided by electricity or natural gas.

Appendix A References

1. Decarb America: Carbon Capture. *Decarb America* https://decarbamerica.org/interactivE–maps/carbon-capture/ (2021).

2. Larson, E. *et al. Net-Zero America: Potential Pathways, Infrastructure, and Impacts, interim report*. (2020).

3. IEA. *Net Zero by 2050: A Roadmap for the Global Energy Sector*. https://www.iea.org/reports/net-zero-by-2050 (2021).

4. Fuss, S. *et al.* Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **13**, 063002 (2018).

5. Keith, D. W., Holmes, G., St. Angelo, D. & Heidel, K. A Process for Capturing CO2 from the Atmosphere. *Joule* **2**, 1573–1594 (2018).

6. National Academies of Sciences, Engineering, and Medicine. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. (National Academies Press, 2019).

7. Hanna, R., Abdulla, A., Xu, Y. & Victor, D. G. Emergency deployment of direct air capture as a response to the climate crisis. *Nat. Commun.* **12**, 368 (2021).

8. Fasihi, M., Efimova, O. & Breyer, C. Techno-economic assessment of CO2 direct air capture plants. *J. Clean. Prod.* **224**, 957–980 (2019).

9. Socolow, R. *et al. Direct Air Capture of CO2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs*. (2011).

10. Keith, D. W., Ha-Duong, M. & Stolaroff, J. K. Climate Strategy with Co2 Capture from the Air. *Clim. Change* **74**, 17–45 (2006).

11. House, K. Z. *et al.* Economic and energetic analysis of capturing CO2 from ambient air. *Proc. Natl. Acad. Sci.* **108**, 20428–20433 (2011).

12. Simon, A. J., Kaahaaina, N. B., Julio Friedmann, S. & Aines, R. D. Systems analysis and cost estimates for large scale capture of carbon dioxide from air. *Energy Procedia* **4**, 2893–2900 (2011).

13. Zeman, F. Reducing the Cost of Ca-Based Direct Air Capture of CO2. *Environ. Sci. Technol.* **48**, 11730–11735 (2014).

14. Sinha, A., Darunte, L. A., Jones, C. W., Realff, M. J. & Kawajiri, Y. Systems Design and Economic Analysis of Direct Air Capture of CO2 through Temperature Vacuum Swing Adsorption Using MIL-101(Cr)-PEI-800 and mmen-Mg2(dobpdc) MOF Adsorbents. *Ind. Eng. Chem. Res.* **56**, 750–764 (2017).