Advancing Geothermal Energy Utilization Opportunities: Potential and Strategies for Integrating Direct Air Capture

Maxwell Pisciotta[a*], Hélène Pilorgé[a], Likhwa Ndlovu[a], Madeleine Siegel[b], Joe Huyett[b], Todd Bandhauer[b], Peter Psarras[a] and Jennifer Wilcox[a]
[a]University of Pennsylvania, Chemical and Biomolecular Engineering Department
[b]Colorado State University, Mechanical Engineering Department

*corresponding author: mpisciot@seas.upenn.edu

S.1 Impact of Total Dissolved Solids (TDS) on Geothermal Brine Heat Exchange

Another consideration for designing a geothermal power plant is the composition of the geothermal brine. Most brines consist of water, dissolved salts, dissolved carbonates, and dissolved gases. The combined dissolved salts and dissolved carbonates are reflected in a parameter, total dissolved solids (TDS). Higher TDS values often inhibit the brine's ability to exchange heat with other fluids, reducing usable geothermal energy. The electricity generation potential for a binary geothermal power plant utilizing 200ºC brine with varying TDS composition is shown in Figure S.1

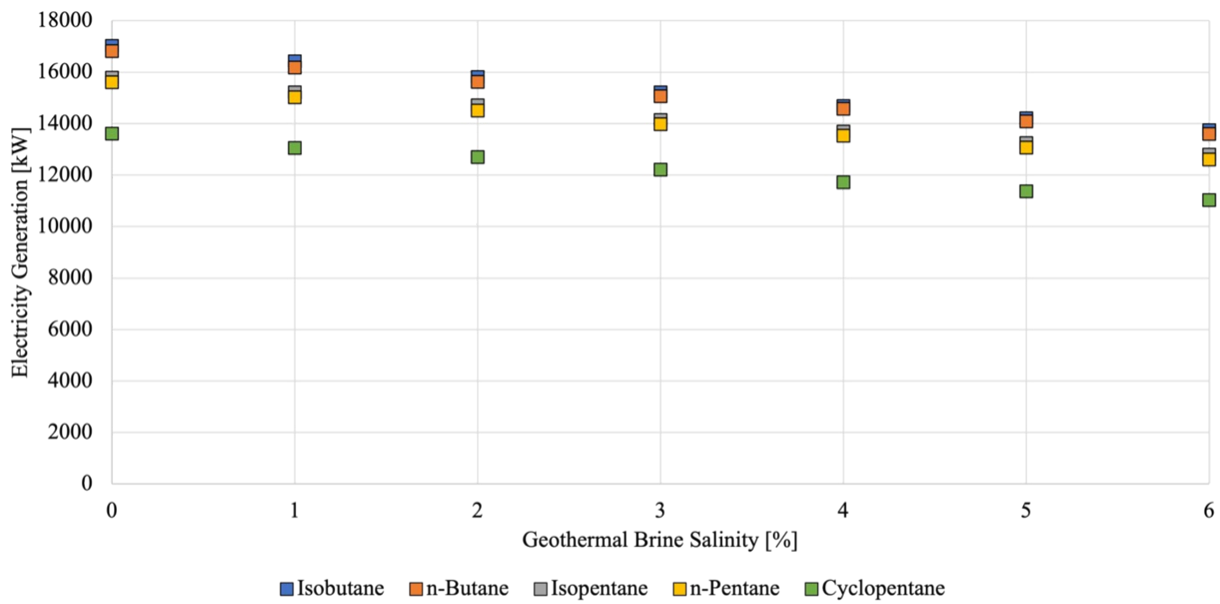


Figure S.1. Electricity generation potential from a 200ºC geothermal reservoir with varying TDS (salinity) using various working fluids. Note 1% salinity is equal to 10,000 ppm TDS.

S.2 Comparison of Various Geothermal-DAC Configurations with Low-Temperature Geothermal Reservoir

For the purpose of side-by-side comparison between the DAC in Parallel and DAC in Series – Upstream for the low-temperature geothermal reservoir, only the data from test cases where the requirements for DAC regeneration are between 80 – 120ºC are considered. Figure S.2 shows the baseline condition where the 86ºC geothermal reservoir is utilized solely for electricity generation, the DAC in Parallel test cases for slip streams 10%, 20%, and 30%, and the DAC in Series – Upstream test case where the DAC regeneration temperature is 81ºC.

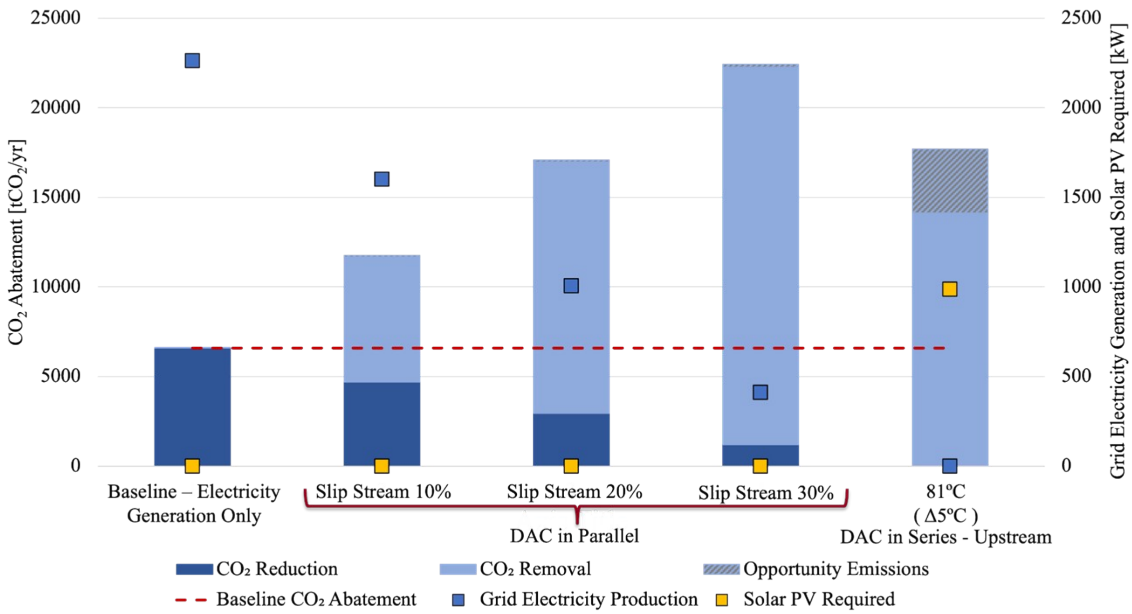


Figure S.2. Side-by-side comparison of various geothermal-DAC configurations utilizing a low-temperature geothermal reservoir at 86ºC, using isobutane as the working fluid. The dark blue bars illustrate the CO_2 reduced via geothermal electricity replacing carbon-intensive electricity on the grid, the light blue bars illustrate the CO_2 removed via the DAC facility, hashed blue bars illustrate the embodied and opportunity cost emissions of the deployed equipment and solar PV dedicated to DAC rather than grid decarbonization, blue square markers indicate the grid electricity generation, and yellow square markers indicate the solar PV required to meet the electricity requirements for the DAC facility. The total CO_2 abatement, height of un-hashed bars can be compared to the baseline CO_2 abatement to see how it compares to the geothermal reservoir being solely used to generate electricity.

S.3 Working Fluid Performance

When the Geothermal-DAC Evaluation Framework was used to evaluate the high-temperature geothermal reservoir at 225ºC, it became evident that working fluids isopentane and cyclopentane outperformed n-pentane. This appendix illustrates some theories as to why this may be the case at higher reservoir temperatures.

First to evaluate the conversion from the liquid state to the vapor state as these different working fluids are superheated by 3ºC in the brine heat exchanger, vapor fraction of the fluid will be what drives the turbine to generate electricity, so higher vapor fractions may elicit higher turbine output. Figure S.3 illustrates the vapor-liquid equilibrium state for each of the working fluids considered held at 9.6 bar with temperature varying from 0 to 250ºC. It can be seen that the vapor fractions of the isopentane and cyclopentane exceed that of the n-pentane after the temperature reaches just over 210ºC, as opposed to below 210ºC, where the vapor fraction for cyclopentane is below that of n-pentane. The greater vapor fraction indicates that less thermal energy is needed to fully vaporize (0ºC superheated) and further superheat this fluid. That results in a higher maximum allowable flow rate for this working fluid, ultimately driving up the electricity generation.

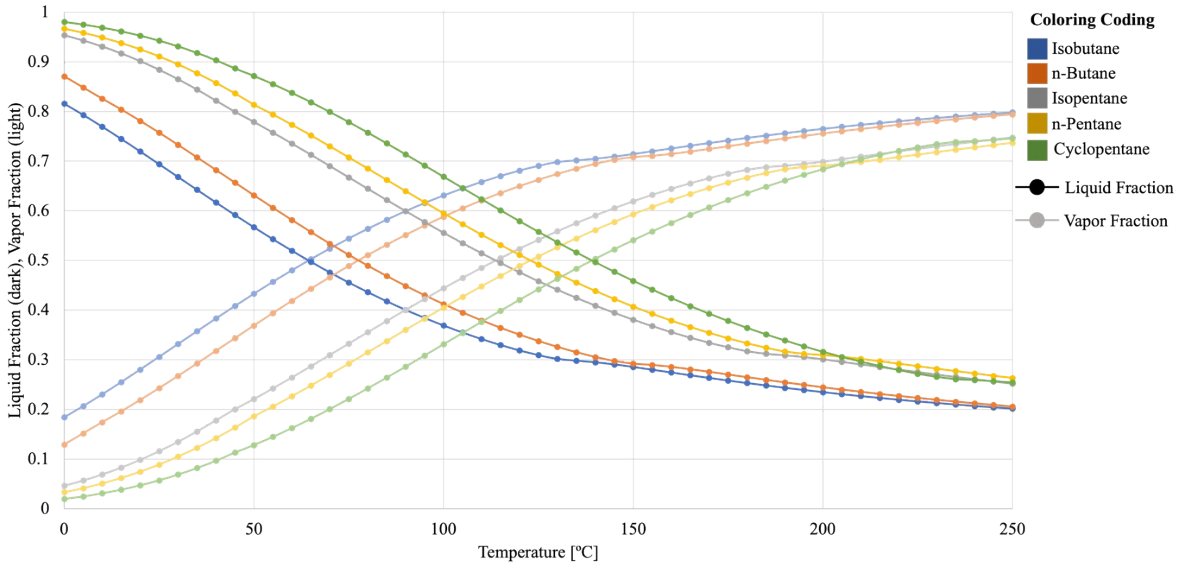


Figure S.3. Liquid and vapor fraction of working fluids at the vapor-liquid equilibrium state held at 9.6 bar with temperature ranging from 0ºC to 250ºC.

S.4 Detailed Results from Geothermal-DAC Configurations with High-Temperature Geothermal Reservoir

Tables S.1 and S.2 show the detailed results from the geothermal-DAC configurations when tested with a high-temperature geothermal reservoir. Table S.1 illustrates the DAC in Parallel case, where the slip stream dedicated to DAC was the sensitivity parameter, and it could be modulated up to 70% for all working fluids except isobutane, which could only be modulated up to 65%, before the geothermal-DAC configuration would have required solar PV to meet electrical requirements for DAC. In each test case, the DAC regeneration temperature is 20ºC less than the production well temperature, resulting in a DAC regeneration temperature of 205ºC.

Table S.1. CO_2 abatement potential for DAC in Parallel configuration with the high-temperature geothermal reservoir using various working fluids

Working Fluid: Isobutane								
DAC Slip Stream	0%	10%	20%	30%	40%	50%	60%	70%
CO_2 Abatement Potential [$ktCO_2$/yr]	39.3	49.8	60.1	68.3	74.8	81.0	87.3	N/A
Improvement	0%	27%	53%	74%	90%	106%	122%	N/A
$LCOE_{DAC}$ [$/$tCO_2$]	-	590	298	207	168	148	140	N/A
$LCOE_{Grid}$ [$/kWh]	0.012	0.014	0.015	0.018	0.024	0.037	0.081	N/A
Working Fluid: n-Butane								
DAC Slip Stream	0%	10%	20%	30%	40%	50%	60%	70%
CO_2 Abatement Potential [$ktCO_2$/yr]	46.7	57.1	67.3	75.1	80.3	85.7	91.0	96.2
Improvement	0%	22%	44%	61%	72%	83%	95%	106%

$LCOE_{DAC}$ [$/t$CO_2$]	-	612	309	213	173	152	143	142
$LCOE_{Grid}$ [$/kWh]	0.01	0.011	0.012	0.014	0.019	0.027	0.050	0.023
Working Fluid: Isopentane								
DAC Slip Stream	0%	10%	20%	30%	40%	50%	60%	70%
CO_2 Abatement Potential [ktCO_2/yr]	55.5	61.2	64.0	72.5	78.1	83.8	89.4	95.1
Improvement	0%	10%	20%	31%	41%	51%	61%	71%
$LCOE_{DAC}$ [$/t$CO_2$]	-	593	313	222	180	158	149	149
$LCOE_{Grid}$ [$/kWh]	0.009	0.010	0.012	0.015	0.020	0.031	0.060	0.474
Working Fluid: n-Pentane								
DAC Slip Stream	0%	10%	20%	30%	40%	50%	60%	70%
CO_2 Abatement Potential [ktCO_2/yr]	54.9	60.4	66.3	72.0	77.7	83.6	89.3	95.0
Improvement	0%	10%	21%	31%	42%	52%	63%	73%
$LCOE_{DAC}$ [$/t$CO_2$]	-	595	314	223	181	159	150	149
$LCOE_{Grid}$ [$/kWh]	0.009	0.10	0.012	0.016	0.021	0.031	0.061	0.546
Working Fluid: Cyclopentane								
DAC Slip Stream	0%	10%	20%	30%	40%	50%	60%	70%
CO_2 Abatement Potential [ktCO_2/yr]	58.2	63.5	69.1	74.4	79.7	85.2	90.6	96.1
Improvement	0%	9%	19%	28%	37%	46%	56%	65%
$LCOE_{DAC}$ [$/t$CO_2$]	-	509	269	192	156	137	130	130
$LCOE_{Grid}$ [$/kWh]	0.008	0.010	0.012	0.014	0.019	0.028	0.053	0.246

Table S.2 illustrates the DAC in Series – Downstream case, where the DAC regeneration temperature was the sensitivity parameter. This parameter was modulated between 80ºC and 120ºC for each working fluid.

Table S.2. CO_2 abatement potential for DAC in Series – Downstream configuration with the high-temperature geothermal reservoir using various working fluids

Working Fluid: Isobutane									
DAC Regeneration Temperature [ºC]	80ºC	85ºC	90ºC	95ºC	100ºC	105ºC	110ºC	115ºC	120ºC
CO_2 Abatement Potential [ktCO_2/yr]	90.7	89.6	88.6	87.5	86.5	85.5	84.4	83.5	82.5
Improvement	132%	130%	127%	124%	122%	119%	116%	114%	111%

$LCOE_{DAC}$ [$/$tCO_2$]	127	129	131	133	135	138	141	144	147
$LCOE_{Grid}$ [$/kWh]	0.024	0.026	0.027	0.029	0.031	0.033	0.036	0.039	0.043
Working Fluid: n-Butane									
DAC Regeneration Temperature [ºC]	80ºC	85ºC	90ºC	95ºC	100ºC	105ºC	110ºC	115ºC	120ºC
CO_2 Abatement Potential [ktCO_2/yr]	88.0	87.1	86.1	85.1	84.2	83.2	82.3	81.4	80.6
Improvement	89%	87%	85%	83%	81%	79%	77%	75%	73%
$LCOE_{DAC}$ [$/$tCO_2$]	130	132	134	137	140	143	146	150	153
$LCOE_{Grid}$ [$/kWh]	0.028	0.030	0.032	0.034	0.037	0.040	0.043	0.047	0.052
Working Fluid: Isopentane									
DAC Regeneration Temperature [ºC]	80ºC	85ºC	90ºC	95ºC	100ºC	105ºC	110ºC	115ºC	120ºC
CO_2 Abatement Potential [ktCO_2/yr]	104.0	102.3	101.0	99.5	97.9	96.5	95.1	93.6	92.2
Improvement	88%	85%	83%	80%	77%	75%	72%	69%	67%
$LCOE_{DAC}$ [$/$tCO_2$]	105	106	108	110	112	114	116	119	121
$LCOE_{Grid}$ [$/kWh]	0.014	0.015	0.016	0.017	0.018	0.019	0.020	0.021	0.023
Working Fluid: n-Pentane									
DAC Regeneration Temperature [ºC]	80ºC	85ºC	90ºC	95ºC	100ºC	105ºC	110ºC	115ºC	120ºC
CO_2 Abatement Potential [ktCO_2/yr]	103.3	101.9	100.4	99.0	97.4	96.0	94.7	93.2	92.0
Improvement	89%	87%	84%	81%	78%	76%	73%	71%	68%
$LCOE_{DAC}$ [$/$tCO_2$]	105	106	108	110	112	114	117	119	121
$LCOE_{Grid}$ [$/kWh]	0.015	0.015	0.016	0.017	0.018	0.019	0.020	0.022	0.023
Working Fluid: Cyclopentane									
DAC Regeneration Temperature [ºC]	80ºC	85ºC	90ºC	95ºC	100ºC	105ºC	110ºC	115ºC	120ºC
CO_2 Abatement Potential [ktCO_2/yr]	106.1	104.7	103.0	101.4	99.9	98.3	96.9	95.4	94.0
Improvement	83%	81%	78%	75%	72%	70%	67%	65%	62%
$LCOE_{DAC}$	101	103	105	107	109	111	113	115	118

[\$/tCO_2]									
$LCOE_{Grid}$ [\$/kWh]	0.014	0.014	0.015	0.016	0.016	0.017	0.018	0.020	0.021

S.5 Geothermal-DAC Configuration Test Cases for Raft River Binary Geothermal Power Plant

Table S.3 summarizes the geothermal-DAC configurations, associated sensitivity parameters and key temperatures throughout the system for the Raft River binary geothermal power plant. In each case, the production well temperature is 137.8ºC and the only working fluid evaluated is the one already used onsite, isopentane. For the DAC in Series – Upstream HP ORC and DAC in Series – Downstream LP ORC, these were not featured in the main body of the paper, as it was not as valuable to utilize these ORCs in conditions they were not optimized for, but the results from these studies are shown further in the Supplementary Information.

Table. S.3. Summary of geothermal-DAC configurations, sensitivity parameters, and temperatures throughout the system for test cases run using the River Raft binary geothermal power plant.

Geothermal-DAC Configuration	Sensitivity Parameter	DAC Inlet Temperature [ºC]	DAC Regeneration Temperature [ºC]	Brine Reinjection Temperature [ºC]
DAC in Parallel	Geothermal brine slip stream dedicated to DAC	137.8ºC	117.8ºC	> 65ºC
DAC in Series – Upstream HP ORC*	Temperature Drop Across the DAC Regeneration Unit	137.8ºC	132.8 – 117.8ºC	> 65ºC
DAC in Series – Upstream LP ORC				
DAC in Series – Downstream HP ORC	DAC Regeneration Temperature	100 – 125ºC	80 – 115ºC	80 – 115ºC
DAC in Series – Downstream LP ORC*				

*Results are not featured in the main body of the paper

S.6 Unconstrained DAC in Parallel Results for Raft River Binary Geothermal Power Plant

Figure S.4 illustrates the decrease in temperature of the brine stream connecting the HP and LP ORCs in the Raft River binary, combined-cycle, geothermal power plant. As the temperature decreases from ~97ºC down to ~94.2ºC, the efficiency, and therefore, relevancy of the LP ORC begins to diminish, indicating the underutilization of the deployed capital. This is further evidenced by Figure S.4b that shows the output from the LP ORC decreasing from ~3.55 MW at 0% DAC slip stream to ~3 MW at 10% DAC slip stream.

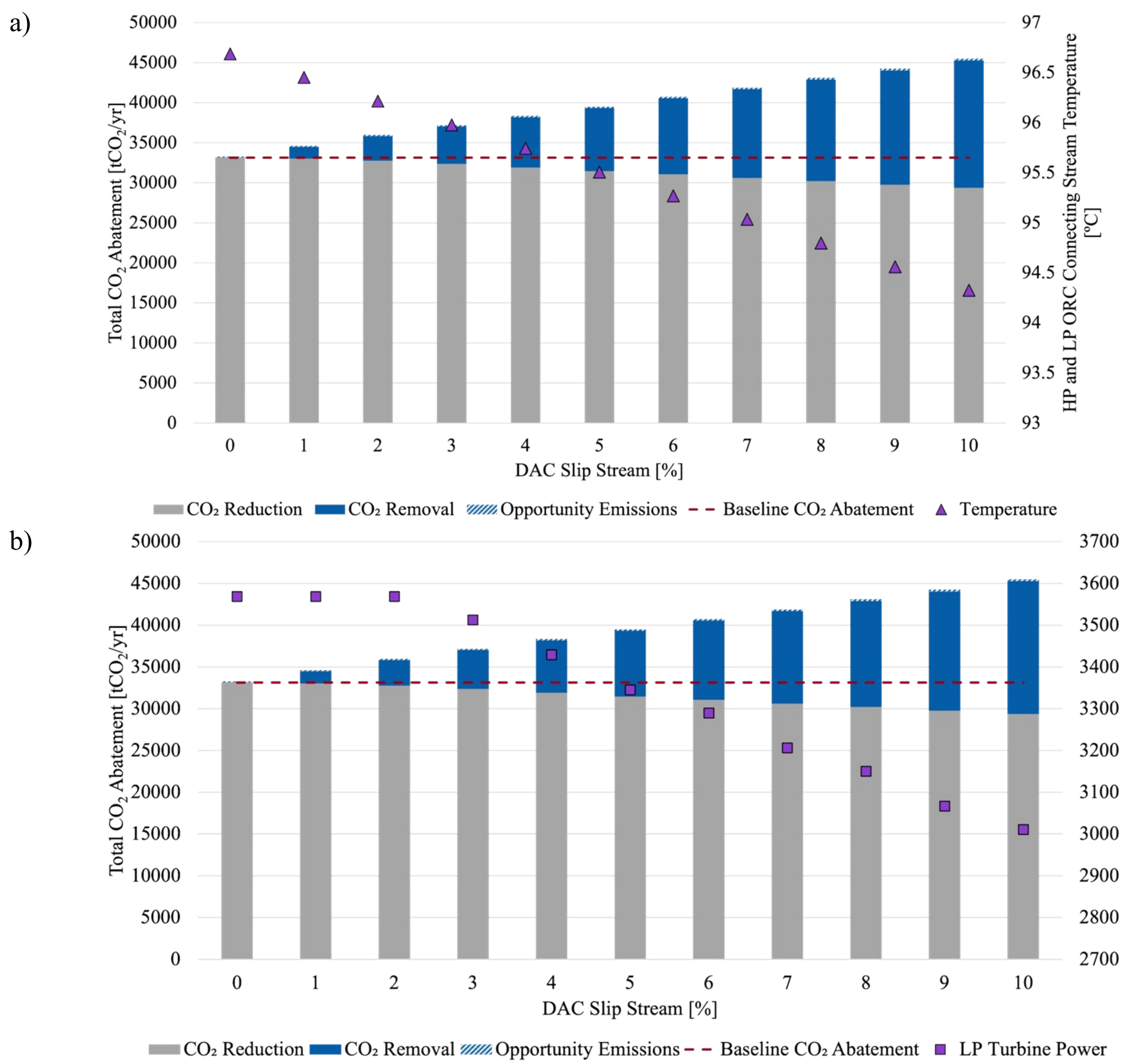


Figure S.4. CO_2 abatement potential from coupling the Raft River geothermal energy power plant with DAC in Parallel with the HP ORC configuration, without constraints, illustrating a) the change in temperature for the stream connecting the HP ORC and LP ORC and b) the LP turbine power capacity. CO_2 abatement potential is determined as the sum of CO_2 displaced from fossil electricity generation (gray bars) and the CO_2 removed by DAC (solid blue bars), after accounting for working fluid, embodied, and opportunity cost emissions (hashed blue bars).

S.7 Coupling DAC in Parallel with River Raft HP ORC

Figure S.5. illustrates the results from integrating DAC with the River Raft binary geothermal power plant that does not have the bottoming cycle. This can be compared to Figure 9 in the main body of the paper, where these results include the bottoming cycle as well. It is notable that the baseline electricity generation is lower (8.6 MW) and therefore the baseline CO_2 abatement is also lower (25.0 ktCO_2/yr). Additionally, we see that that maximum slip stream available for DAC is only 55%, whereas, it is 75% with both ORCs.

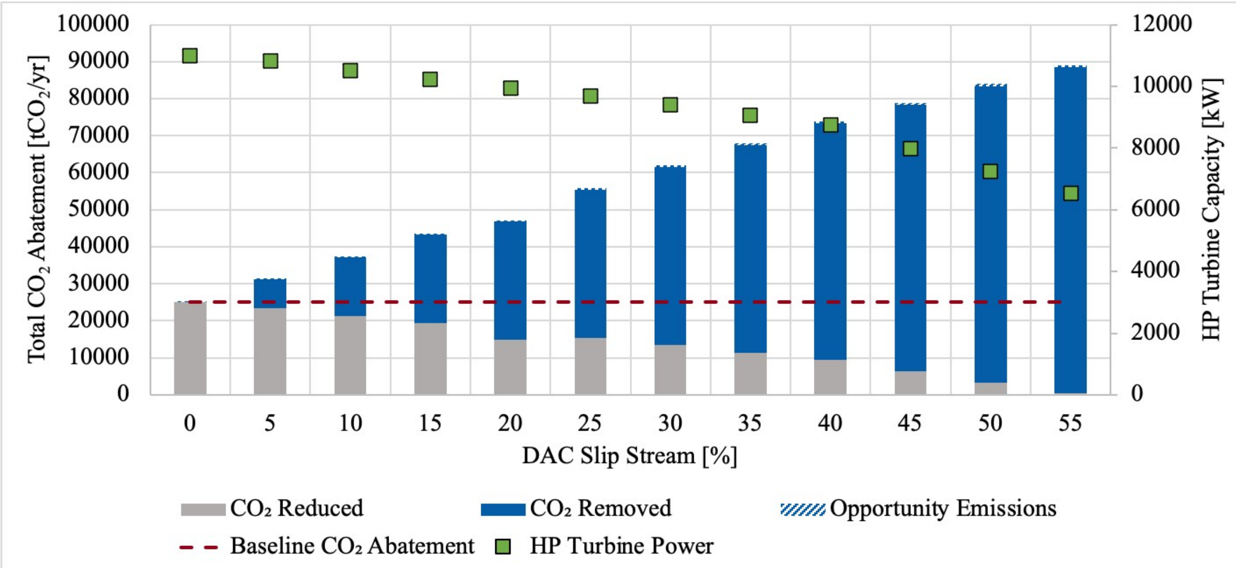
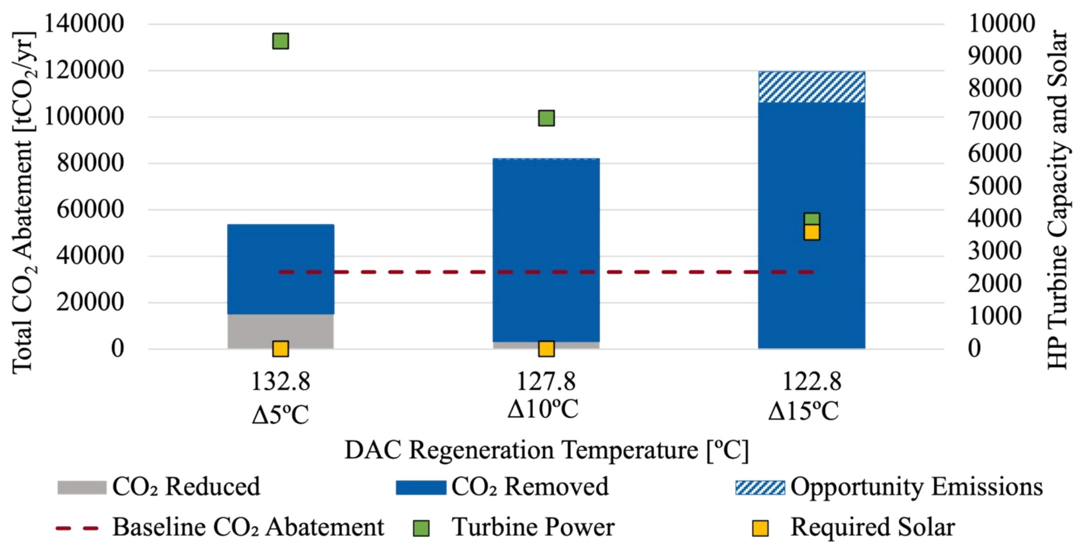


Figure S.5. CO_2 abatement potential from coupling the River Raft HP ORC with DAC in Parallel, constraining the reinjection temperature. CO_2 abatement is determined as the sum of CO_2 displaced from fossil electricity generation (gray bars) and the CO_2 removed by DAC (solid blue bars), after accounting for working fluid, embodied, and opportunity cost emissions (hashed blue bars).

S.8 Results from DAC in Series - Upstream of High-Pressure ORC

In Figure S.6 it can be seen that as the DAC regeneration temperature decreases (which coincides with more heat loss in the DAC regeneration unit), the turbine power generated decreases, illustrating less enthalpy for the ORC to convert to electricity. Once the DAC regeneration temperature reaches 122.8ºC (15ºC lower than the production well temperature) the HP ORC no longer meets the electricity demands of DAC and nearly 3.6 kW of solar must be deployed to sustain this configuration.

a)



b)

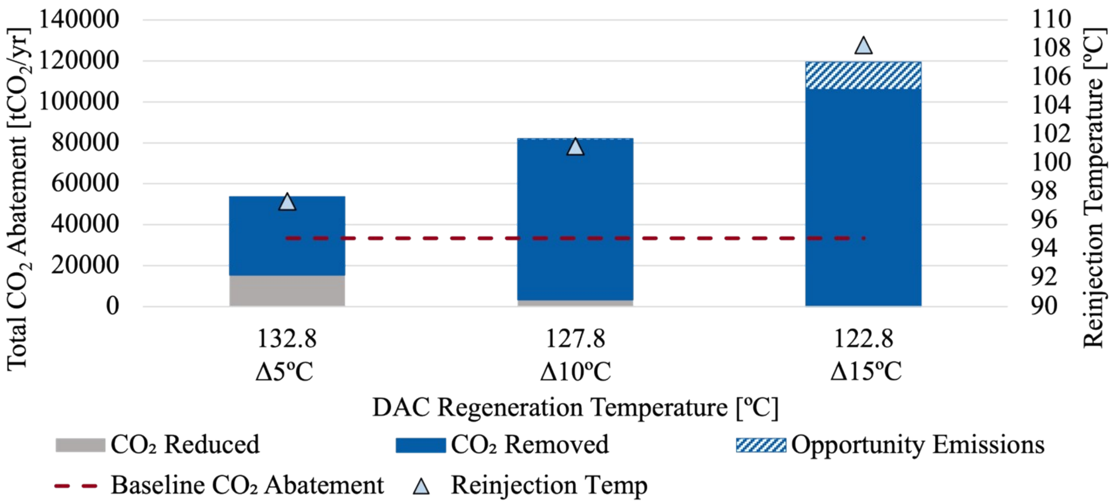


Figure S.6. CO_2 abatement potential for DAC in Series – Upstream of the HP ORC configuration with a) showing turbine power and needed solar deployment to meet DAC electricity requirements and b) showing the reinjection well temperature in each test case. Various regeneration temperature were tested, all within 20ºC of the production well temperature.

Operating DAC upstream of the HP ORC decreases the efficiency of the HP ORC because it was designed to convert high-enthalpy brine to electricity, while now it is operating using lower enthalpy brine. This is illustrated in Figure S.6b. As the DAC regeneration temperature decreases (which coincides with more heat loss in the DAC regeneration unit), the reinjection well temperature increases from the initial 97ºC to 108ºC, both of which are well above the baseline 77.7ºC. These elevated temperatures are a direct result of the HP ORC being unable to make use of the brine enthalpy between the baseline reinjection temperature at 77.7ºC and the reinjection temperature at each of the cases tested.

Despite the loss of efficiency in the HP ORC due to DAC utilizing the high-enthalpy brine and the deployment of solar PV to meet the electricity needs of DAC, the total CO_2 abatement potential of all the tested cases is higher than the baseline 33.1 ktCO_2/yr, achieved by producing electricity alone. In the case where the DAC regeneration temperature is 132.8ºC (5ºC lower than the production well temperature), the total CO_2 abatement potential is 53.3 ktCO_2/yr, an improvement of 161% over baseline, while also being able to deliver 5.2 MW of power to the grid. Even when solar PV is deployed in the case where the DAC regeneration temperature is 122.8ºC (15ºC lower than the production well temperature), the total CO_2 abatement potential is 106.2 ktCO_2/yr, an improvement of 320% over baseline.

Furthermore, these results can be compared to the same DAC regeneration temperature in the DAC in Series - Upstream of the HP ORC configuration to illustrate the increased efficiency of this configuration. When the DAC regeneration temperature is 132.8ºC (5ºC below the production well temperature), the total CO_2 abatement for the DAC in Series - Upstream of the HP ORC is estimated to be 53.3 ktCO_2/yr, while this one is 57.3 ktCO_2/yr, illustrating an 8% improvement by using the LP ORC. When the DAC regeneration temperature is 122.8ºC (15ºC below the production well temperature), the total CO_2 abatement for the DAC in Series - Upstream of the HP ORC is 106.2 ktCO_2/yr, while this one is 119.6 ktCO_2/yr, a 13% improvement. The increased improvement between these two cases can be attributed to the necessity for solar PV when considering the DAC in Series - Upstream of the HP ORC configuration at the same DAC regeneration temperature.

S.9 Results from DAC in Series - Downstream of the Low- Pressure ORC

The DAC regeneration step downstream of the ORC was also evaluated for the LP ORC. The trends for this configuration follow the same trends as the one which DAC downstream of the high pressure ORC and are presented in Figure S.7. As the DAC regeneration temperature increases, the turbine power decreases, the need to deploy solar PV increases, and by virtue, the opportunity emissions increase. However, the LP ORC is unable to produce enough electricity to fully meet the electricity demand of the DAC plant in the DAC regeneration temperature range tested here. This is because the LP ORC is designed to utilize lower enthalpy geothermal brine than it is being provided in this configuration, and so, must rely on the deployment of solar PV to meet the full electrical demands.

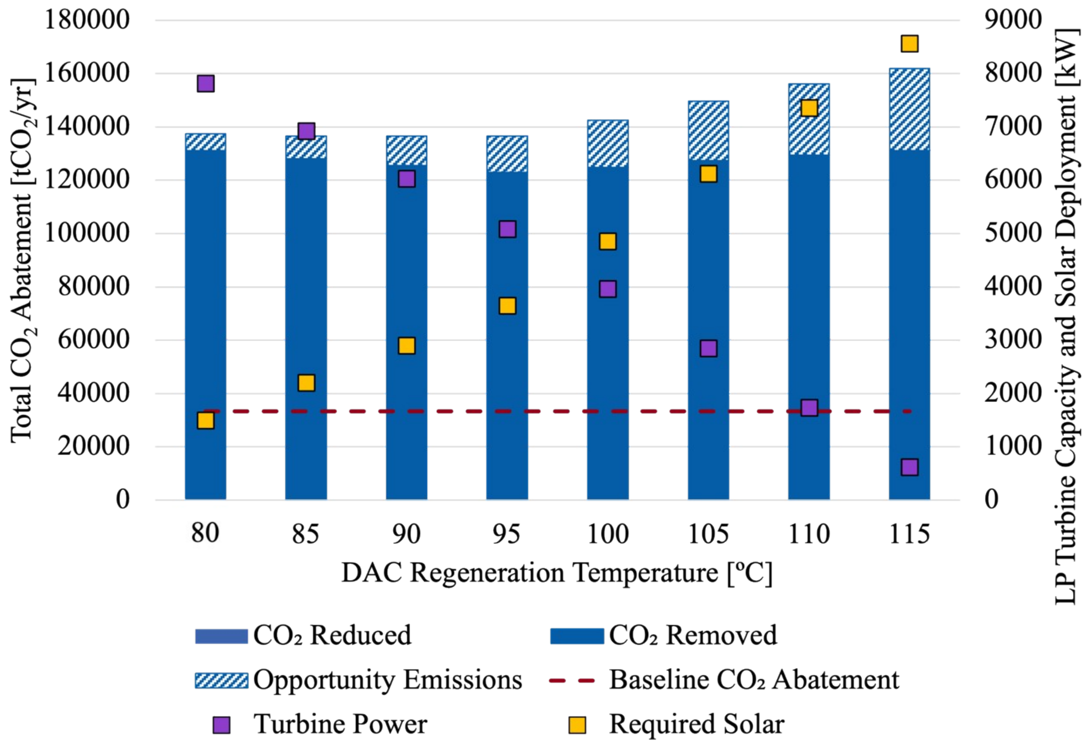


Figure S.7. CO_2 abatement potential for DAC in Series – Downstream of LP ORC configuration from the River Raft binary geothermal power plant. Note the reinjection well temperature is synonymous with the DAC regeneration temperature.

Despite requiring additional renewable buildout for meeting the electricity requirements, the CO_2 abatement in each of the test cases for DAC in Series - Downstream of the LP ORC results in more CO_2 abated as compared to the baseline case of 33.1 $ktCO_2$/yr. The minimum CO_2 abated occurs at the lowest DAC regeneration temperature (80ºC), resulting in 130 $ktCO_2$/yr, illustrating an improvement of 394% over baseline. The maximum CO_2 abatement occurs at the highest DAC regeneration temperature (115ºC) at 131 $ktCO_2$/yr, an improvement of 396% over baseline. Similar to the previous analysis comparing the net CO_2 abatement to the opportunity cost emissions for each test case, a similar trend is present. At the minimum CO_2 abatement test case, with a DAC regeneration temperature of 80ºC, the opportunity cost emissions are 6.20 $ktCO_2$/yr, while in the maximum CO_2 abatement test case, with a DAC regeneration temperature of 115ºC, the opportunity cost emissions are 30.8 $ktCO_2$/yr. This illustrates a net benefit of 1$ktCO_2$/yr improvement at the cost of 24.6 $ktCO_2$/yr in opportunity cost emissions.