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Combining Direct Air Capture and Geothermal Heat and Electricity Generation for Net-negative Carbon Dioxide Emissions

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ABSTRACT

In this work, Direct Air Capture (DAC) of CO_2 is coupled directly with a sedimentary geothermal system with the goal of creating a stand-alone, carbon-negative CO_2 capture system. An isobutane Organic Rankine Cycle (ORC) is used to generate electricity from a 2.5 km deep, 50 mD porous-media reservoir with a temperature ranging from 90°C to 140°C. The heat required by the DAC is extracted directly from the produced geothermal stream. A 1 km^2 inverted 5-spot reservoir configuration is used. Four different system configurations are tested, including different ORC configurations and the use of an external electrical supply.

We find that Direct Air Capture and a geothermal cycle can be coupled in a stand-alone power-island to capture up to 0.04 MtCO_2 per year with a 140°C reservoir and the given 1 km^2 reservoir configuration. When 12 MW_e of external power is supplied, possibly from a nearby wind turbine farm or photovoltaic park, the same combined system can capture up to 0.18 MtCO_2 per year. If a thirty year system lifetime is assumed, the systems can capture from 1.2 MtCO_2 to 5.4 MtCO_2 over the system lifetime. Also, as the 5-spot reservoir system is designed to be up-scaled by tiling additional 5-spots together into larger configurations without thermal or pressure interference, we considered coupling a 5 km x 5 km geothermal reservoir with Direct Air CO_2 Capture as well. When using this 25 km^2 reservoir, the stand-alone power island system captures 1.04 MtCO_2 per year while the grid-connected system captures 4.63 MtCO_2 per year using 282 MW_e of externally supplied electricity.

Additionally, we find that there is a temperature optimum for the geothermal resource at which the ORC and steam generator both provide the required proportions of heat and electricity to the DAC. At higher resource temperatures, additional electricity is needed for the DAC, either from a parallel ORC or from an external source. At lower resource temperatures, necessary additional heat for the DAC is provided via an isobutane Heat Pump (HP). With the current assumption of an adsorption-based DAC process whose heat demand is provided through saturated steam at atmospheric pressure, a temperature of 110°C is most ideally suited. Lastly, we find that most resource temperatures have an electric opportunity cost—the forgone electricity per tonne CO_2—of approximately 700 kW_e-h per tonne CO_2.

1. INTRODUCTION

Direct Air Capture (DAC) removes CO_2 directly from the atmosphere and therefore is a key technology to mitigate climate change by enabling negative CO_2 emissions (IPCC, 2014). When DAC is combined with (geologic) storage of the captured CO_2, it is referred to as DACS. However, due to the low concentration of ambient CO_2, DAC is inherently energy intensive. For instance, adsorption-based DAC processes require approximately 500 kW_e-h of electricity and 1500 kW_{th}-h of thermal energy to capture one tonne of CO_2. If the carbon intensity of its energy source is low, neutral, or negative, the combined Direct Air CO_2 Capture system can be a net-negative carbon emitter. Thus, we couple a Direct Air Capture unit with a carbon-neutral geothermal power plant with the objective of creating a standalone, autarkic system.

In this work, we find the CO_2 capture rate, power requirements, and electric opportunity cost for a sedimentary hydro-geothermal system coupled with Direct Air Capture (geo-DAC). This system could be used to capture CO_2 to fill the 1 km^2 reservoir of a CO_2 Plume Geothermal (CPG) system with the 2 to 3 MtCO_2 necessary (Randolph & Saar, 2010; 2011; Garapati et al., 2016). The heat required by the DAC units is supplied directly from the produced geologic fluid while electricity is generated by ORCs. We intentionally focus on low-grade geothermal resources in order to study the widespread use of geo-DAC for Carbon Dioxide Removal (CDR) applications including remote locations without grid connection and, consequently, assuming island operation.

2. METHODS

A sedimentary geothermal system is coupled with Direct Air CO_2 Capture (DAC) using four configurations ("Systems"), plus a reference configuration, given in Table 1. Corresponding system diagrams are in Figure 1. The top-listed system, *Reference*, is the geothermal electricity generated without DAC, and it is a comparison for all other configurations. *Systems 1 through 4* are different combinations of coupling geo-DACS. Isobutane Organic Rankine Cycles (ORC) are used to generate electricity from the produced geothermal water. An isobutane Heat Pump is used to augment the temperature of the geothermal fluid at low resource temperatures.

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2.1 System Overview

The minimum useful temperature of the DAC system applied here is 105°C, as we assume that steam at atmospheric pressure is used. Thus, the systems tend to be configured such that steam generation occurs with higher temperature geothermal fluid and electricity generation is optimized to use the remaining heat.

Table 1: System Configurations

Name	Components	Description
Reference	ORC	A reference ORC for comparison which generates electricity without DAC.
System 1	DAC, Bottoming ORC	A basic grid-connected system that takes grid electricity when needed.
System 2	DAC, Bottoming ORC, Heat Pump (Low-T), Parallel ORC (High-T)	An island system that uses all geothermal heat to capture CO_2. Uses a heat pump for low production temperatures and a parallel-connected ORC for high temperatures.
System 3	DAC, Bottoming ORC, Heat Pump (Low-T), Excess Grid Power (High-T)	An island system that uses all geothermal heat to capture CO_2. Uses a heat pump like *System 2*, however takes surplus electricity from a neighboring wind farm at high production temperatures.
System 4	DAC, Bottoming ORC, Heat Pump (Low-T), Serial Topping ORC (High-T)	An island system like *System 2*; however, at high production temperatures, a second ORC is serially-connected upstream of the DAC.

System 1 is a basic combination of DAC and ORC. All geothermal heat above 105°C generates steam for the DAC and the remainder of heat is used in a bottoming isobutane ORC cycle. As the amount of heat and electricity generated do not match the requirements of the DAC system exactly, all heat is transferred from the boiler to DAC and power is taken-from and sent-to the electricity grid as needed.

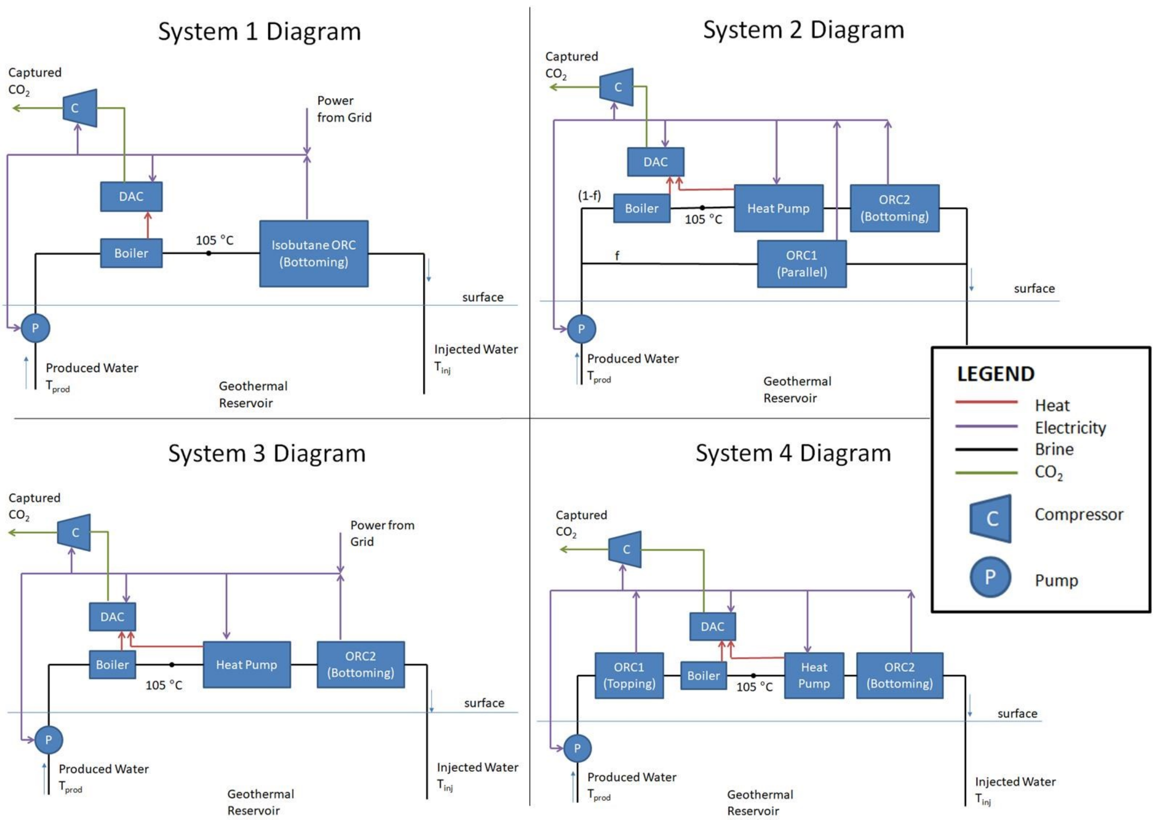

Figure 1: System schematic of the four system types simulated.

System 2 is an improvement upon *System 1* whereby the system is isolated from the electric grid. At low geothermal production temperatures, little or no steam is generated, requiring a heat pump to generate the required steam. At high geothermal production temperatures, a second parallel ORC is added to generate the required electricity for the ample steam supply.

System 3 is the coupling of this system with an external source that can supply, but not accept electricity (e.g. a dedicated wind farm without grid connection or excess renewable electricity that would otherwise be curtailed). Thus, at low geothermal production temperatures, a heat pump is used to generate the necessary steam; while at high geothermal production temperatures, the required electricity is supplied externally.

System 4 is similar to *System 2*, except the second ORC is installed in series in the geothermal fluid stream instead of in parallel. This configuration might save exergy which would otherwise be destroyed in the steam generator due to large temperature differences by using an ORC with higher evaporator temperature, and thus a smaller temperature difference within the steam generator.

2.2 Geologic Model

This geothermal system uses a 2.5 km deep sedimentary reservoir filled with water. All simulation parameters are given in Table 2. The reservoir temperature varies between 90°C and 140°C, corresponding to geologic temperature gradients of 30°C/km to 50°C/km. Four vertical production wells and one central vertical injection well are used in a typical 1 km^2 inverted 5-spot well pattern. The reservoir pressure at the production well downhole is hydrostatic (24.5 MPa), while the injection well downhole pressure is higher. The reservoir production temperature is assumed constant at the initial reservoir temperature.

Table 2: Simulation Parameters

Parameter	Value
Reservoir Depth	2.5 km
Geologic Temperature Gradient	30°C/km to 50°C/km
Ambient Temperature	15°C
Reservoir Temperature	90°C (30°C/km) to 140°C (50°C/km)
Reservoir Pressure	24.5 MPa (hydrostatic)
Reservoir Permeability	50 mD
Reservoir Thickness	305 m
Reservoir Configuration	Inverted 5-spot (1 km^2)
Reservoir Fluid	Water
Well Spacing	707 m
Well Diameter	0.4 m
Pipe Roughness	55 μm
Downhole Production Well Pump Depth	500 m
ORC Working Fluid	Isobutane (R600a)
ORC Design	Single Pressure, No Superheat
Heat Pump Working Fluid	Isobutane (R600a)
Heat Pump Design	Single Pressure, Throttle Expansion
Compressor Design	4-stage with Inter-stage Cooling
Compressor Exit Pressure	6 MPa
Pump Isentropic Efficiency	90%
Turbine Isentropic Efficiency	80%
Compressor Isentropic Efficiency	80%
Heat Exchanger Pinch Point, minimum	5°C
Cooling Tower Type	Wet, forced convection
Cooling Tower Approach Temperature	5°C
DAC Design	Adsorption
DAC Thermal Load	1500 kW_{th}-h /tCO_2
DAC Electric Load	500 kW_e-h /tCO_2
DAC CO_2 Exit Temperature	15°C
DAC CO_2 Exit Pressure	0.1 MPa
Geofluid Mass Flow Rate	Variable; maximizes reference ORC power.

A 1-D Darcy approximation for a 5-spot is used to estimate the reservoir impedance, *I*, and thus the pressure difference between injection and production wells, *ΔP*, for a given water mass flow rate, $\dot{m}$, given in Equation 1.

$$I = \frac{\Delta P}{\dot{m}} = \frac{\mu}{\rho \kappa b} \ln\left(\frac{4L}{D\pi}\right) \quad (1)$$

The dynamic viscosity, μ, and density, ρ, are determined from the average of water properties at hydrostatic pressure and temperatures of 15°C and the reservoir temperature. The reservoir permeability, κ, thickness, b, well spacing, L, and pipe diameter, D, are given in Table 2. The constant π is the geometric constant. For example, at a reservoir temperature of 100°C, the reservoir impedance is 250 kPa-s/kg.

Downhole production pumps are positioned at a depth of 500 m to maintain the water entering the pumps in a liquid state. Likewise, the surface water pressure is maintained 100 kPa above the vapor pressure at the reservoir temperature. At no time does a minimum pressure for liquid water limit the flow rates or temperatures of the simulations.

2.3 DAC, ORC, and HP Models

The Organic Rankine Cycle (ORC) is a single pressure system using isobutane (R600a). The condensation temperature is set at 5°C over ambient temperature. The evaporation temperature is optimized for every simulation to produce the highest net electricity. The turbine inlet state is saturated vapor and the pump inlet state is saturated liquid. The evaporator and preheater heat exchanger designs keep the minimum pinch temperature difference between the isobutane and water at 5°C. Other relevant parameters are given in Table 2.

The Heat Pump (HP) is a single pressure system using isobutane (R600a). The condensation temperature is set to 5°C greater than the vapor temperature of ambient pressure water (105°C). The compressor inlet is saturated vapor and the throttle inlet is saturated liquid. The heat addition is therefore all at constant temperature and the evaporator temperature is set to 5°C less than the water exit temperature.

The net power generated by the ORC is the gross turbine power less both: the isobutane pump power and the parasitic fan loads of the condensing and cooling towers. The parasitic fan loads are determined from Adams et al. (2015). The HP has no parasitic power loads, thus the power required by the heat pump is equivalent to the heat pump compressor power. The isobutane cycles are subcritical, thus, the evaporator and condenser temperatures are maintained below the isobutane critical temperature of 134.6°C.

The Direct Air CO_2 Capture unit requires 500 kW_e-h per tonne of CO_2 captured. Additionally, the DAC requires ambient pressure steam, thus 1500 kW_{th}-h per tonne of CO_2 is required, where the heat source is at minimum 105°C, assuming a steam generator minimum heat exchanger pinch point temperature of 5°C.

CO_2 compression occurs by way of a four-stage compressor with 80% isentropic efficiency and inter-stage cooling. The inlet temperature of the compressor is 0.1 MPa and the outlet is 6 MPa. A CO_2 pressure of 6 MPa at ambient temperature has been shown to be sufficient to overcome downhole reservoir injection pressures of a 2.5 km reservoir due to its high CO_2 density (Adams et al., 2014). The temperature after each intercooler is 5°C above ambient temperature. The pressures at each intermediate stage were determined through optimization to minimize the compression power with the fixed number of stages.

2.4 Reference ORC

For comparison of all geo-DAC systems, a reference ORC was used. The reference ORC is the net power generated by the geothermal system if no DAC was present.

The reference system determines the geologic water mass flow rate used in all subsequent simulations. For a given ORC, the electricity generated varies linearly with mass flow rate of water through it. However, the pumping power necessary to circulate the geologic fluid increases with mass flow rate to the power of 2.5, due to the wellbore pipe frictional pressure losses (Adams et al., 2015). Thus, an optimum mass flow rate exists which has the highest power generated for a resource temperature. The optimum mass flow rate and reference power generated are shown in Figure 2.

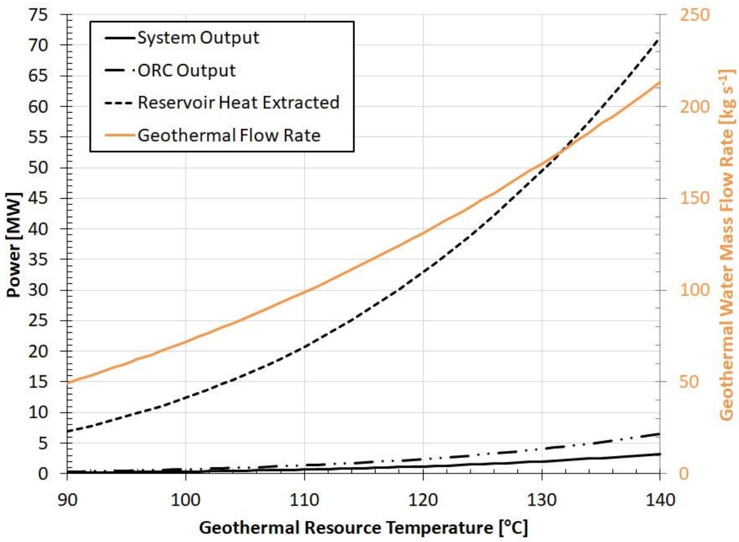

Figure 2: Reference ORC electric power output, thermal energy extracted from the reservoir, and geothermal water mass flow rate.

The reference power (i.e. "System Output") generated for a specific geothermal resource temperature is the net power generated by the ORC less the power required by the downhole water pumps. The water pump power is the difference between "System Output" and "ORC Output" in Figure 2. Additionally, the heat input extracted from the geothermal reservoir is also shown in Figure 2.

The thermal efficiency of the reference ORC varies from 5% to 9% for temperatures of 90°C and 140°C, respectively. When the water pumping power is included, the thermal efficiency of the entire reference geothermal system decreases to 2.5% and 4.5% for temperatures of 90°C and 140°C, respectively.

3. RESULTS

Figure 3 shows the CO_2 captured and electricity requirement of *System 1*.

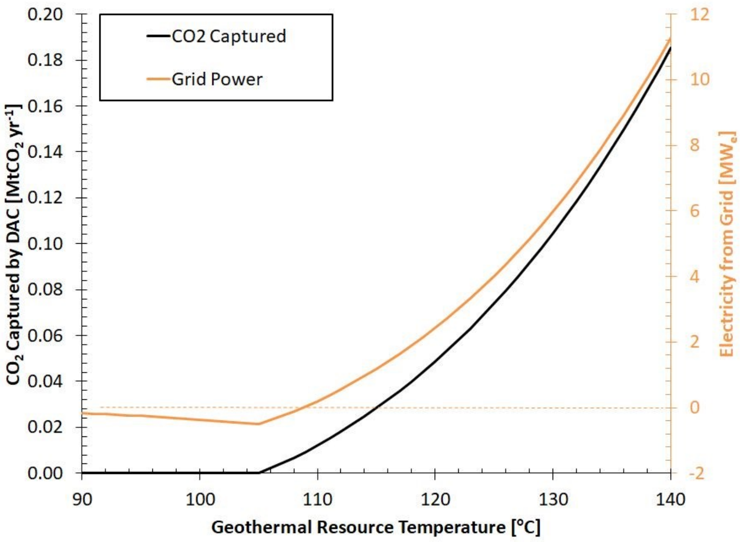

Figure 3: CO_2 Captured by System 1 for Varying Resource Temperature

System 1 has only a steam generator and bottoming ORC. As the minimum temperature required to generate steam is 105°C, the DAC does not operate below a resource temperature of 105°C, but instead electricity is generated and sent to the grid. At temperatures above 105°C, the DAC operates and captures CO_2. At a resource temperature of approximately 109.5°C, the power requirement of the DAC is equal to that generated by the ORC and no electricity is exchanged with the electric grid. At temperatures above 109.5°C, the thermal power captured by the steam generator is high, generating higher quantities of CO_2, but also requiring external electricity from the grid to operate.

System 2 is an improvement of *System 1* where no external electricity is needed from the grid. The results for *System 2* are shown in Figure 4.

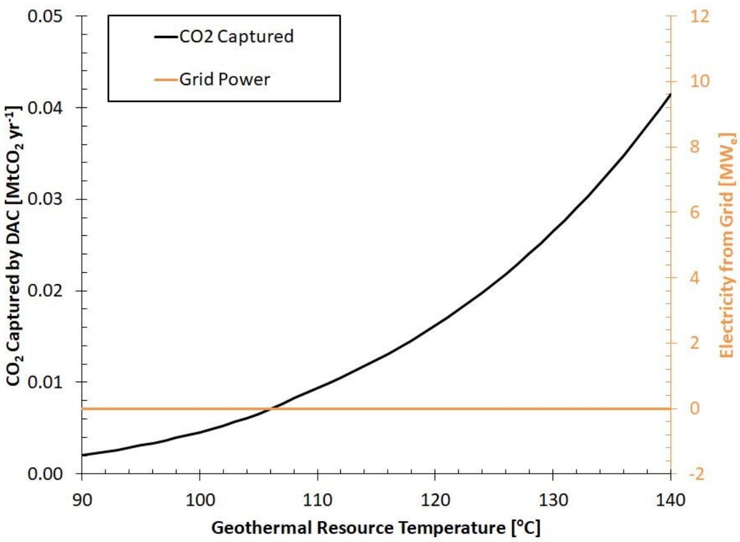

Figure 4: CO_2 Captured by System 2 for Varying Resource Temperatures

At low resource temperatures, where not enough heat is supplied by the geothermal stream, a heat pump is used to elevate the low temperature geologic fluid and boil water. The electricity to drive the heat pump and downhole pumps is generated in the bottoming ORC. At high temperatures, a separate, parallel ORC generates the additional electricity needed by the DAC.

Figure 5 shows that substantial power is generated by the primary, parallel ORC at high resource temperatures. At a resource temperature of 140°C, 77% of the produced water is diverted through the parallel ORC, while only 23% is used in the steam generator and bottoming ORC. Also, the downhole water pumping power requirement is approximately half the power generated by the ORCs in most cases. The CO_2 compression power is negligible due to the relatively small mass flow rate of CO_2 captured compared to the mass flow rate of geothermal water and the corresponding pumping requirements.

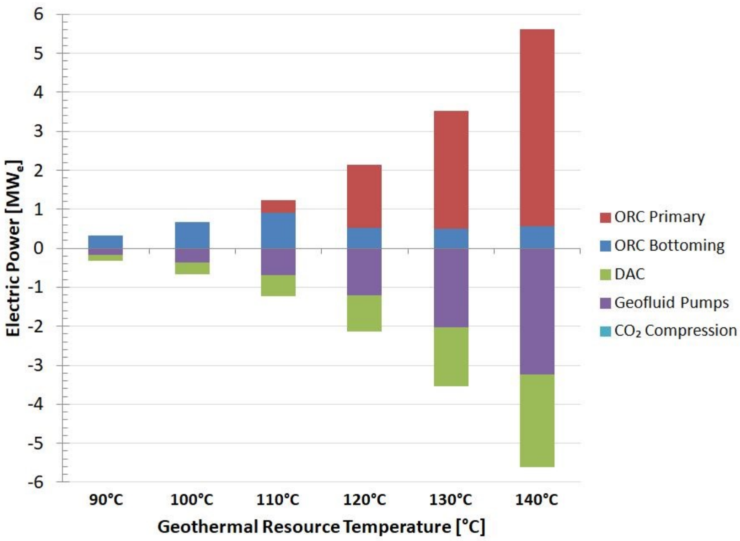

Figure 5: Electric Power Breakdown of System 2.

Figure 6 shows the CO_2 captured and electricity used in *System 3*. *System 3* uses an external electricity source, such as a wind turbine. As the amount of power is no longer constrained by that of the geothermal resource, much more CO_2 can be captured in this configuration. At low resource temperatures, a heat pump is used to generate steam. The heat pump is powered by the bottoming ORC and the import of electricity is zero up to reservoir temperatures of 110°C (see Figure 6).

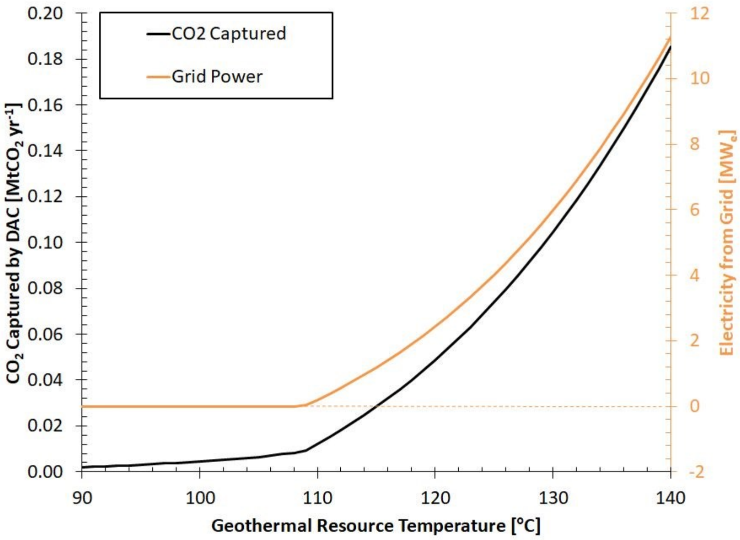

Figure 6: CO_2 Captured by System 3 for Varying Resource Temperatures

Lastly, *System 4* is an improvement upon *System 2*, where the parallel ORC was moved upstream of the steam generator. This was done to limit the exergy destruction in the steam generator due to the high difference in heat exchanger temperature between the 100°C boiling water and the resource temperature. *System 4* uses no external power. All four systems are compared in Figure 7.

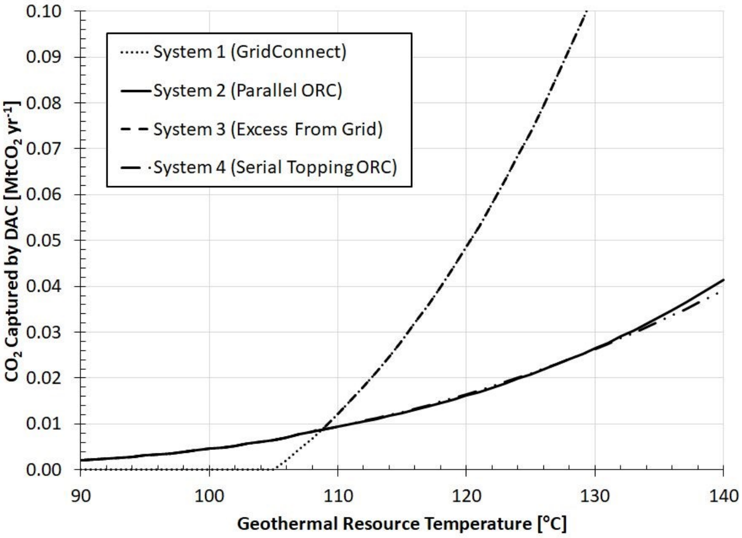

Figure 7: CO_2 Captured by Systems 1 through 4 for Varying Resource Temperatures

The CO_2 captured by *System 4* is very similar to that of *System 2*, slightly decreasing at high resource temperature. It was hypothesized that positioning the primary ORC upstream of the DAC would increase the boiling temperature of the ORC, increase the ORC thermal efficiency, and better utilize the high-temperature resource. This is partially correct as the primary ORC thermal efficiency increased from 9.1% to 11.7% at a 140°C resource temperature when *System 4* is used instead of *System 2*. However, the unexpected consequence of *System 4* is the increase in utilization of the bottoming ORC which has a thermal efficiency of 6.2% due to its low inlet temperature of 105°C. Thus, the *System 4* ORC configuration ultimately has nearly the same effective thermal efficiency and captures approximately the same CO_2 as *System 2*. Overall, the direct use of the geothermal heat in the DAC system is relatively efficient, even at higher resource temperatures where the ΔT in the heat exchanger is high.

Both *Systems 1 and 3* have substantially larger CO_2 capture at high resource temperature than the others due to the imported electricity from the grid. At resource temperatures below 105°C, the capture of CO_2 is only through the use of a heat pump.

3.1 Electric Opportunity Cost

For a cost metric, the electric opportunity cost, C_{eo}, is used. The electric opportunity cost is the amount of electricity that could have been sold to the grid in a geothermal-only configuration divided by the CO_2 captured, given in Equation 2.

$$C_{\text{eo}} = \frac{(\dot{W}_{\text{ref}}+\dot{W}_{\text{grid}})\cdot 8760\frac{\text{hr}}{\text{yr}}}{M_{\text{CO}_2}} \quad (2)$$

The cost, C_{eo}, has units of kW_e-h /tCO_2, where $\dot{W}_{\text{ref}}$ is electric generation of the reference ORC [kW_e], $\dot{W}_{\text{grid}}$ is the power imported from the electric grid [kW_e], and M_{CO_2} is the mass of CO_2 captured per year [tonnes/yr]. Table 3 shows the electric opportunity cost for *Systems 2 and 3* for resource temperatures between 90°C and 140°C.

Table 3: Electric Opportunity Cost

Resource Temperature [°C]	C_{eo} (*System 2*: Power Island) [kW_e-h/tCO_2]	C_{eo} (*System 3*: External Power) [kW_e-h/tCO_2]
90	731	731
100	694	694
110	644	644
120	658	657
130	673	671
140	689	688

For both systems, the electric opportunity cost is typically below 700 kW_e-h /tCO_2. The lowest opportunity cost is near resource temperatures of 110°C, where the steam generator and bottoming ORC naturally produce the correct proportions of heat and electricity, respectively, for the DAC.

For both systems, the electric opportunity cost is the same, even though *System 3* captures more CO_2 than *System 2.* At a resource temperature of 140°C, *System 3* captures more CO_2 than *System 2* by a factor of 4.5. At this temperature, in *System 2*, the mass flow rate through the DAC leg is 48 kg/s and the mass flow rate through the parallel ORC leg is 165 kg/s. However, when external grid power is supplied, the DAC leg of the system operates with the same state points, but with the higher combined mass flow rate of 213 kg/s. Thus, the flow rate through the DAC leg is increased by a factor of 4.5 in *System 3* and the CO_2 captured increases by a factor of 4.5. However, as the state points of the DAC leg are identical in both systems, the electric opportunity cost per tonne CO_2 captured is also the same.

3.2 Build-out and Scalability to Larger Configurations

The geothermal reservoir being considered thus far is a single 5-spot reservoir with a 1 km^2 reservoir area. However, the extensive nature of sedimentary basins is different from traditional fracture-based geothermal and allows for uniform, dispersed heat extraction, and therefore up-scaling. Additionally, the no-flow heat and mass boundaries of the inverted 5-spot reservoir allow for the co-placement of multiple adjacent 5-spots without thermal or pressure interference. In addition to increasing the geothermal power available, scaling-up these reservoirs to a 5 km x 5 km size has shown to be an economic minimum, reducing the overall cost of electricity by sharing production wells between 5-spots while using a single surface power plant (Bielicki et al., 2016). Thus, we consider up-scaling the 5-spots to higher configurations here.

Table 4 shows the configuration number, reservoir area, and up-scaled CO_2 capture rates for a 140°C resource temperature. Each reservoir area is a square where the configuration number is length of one side in kilometers. While multiple 5-spot reservoirs are used in large configuration numbers, all wells are piped to a single, central surface power plant. We assume that the capture rate and external power scales linearly with reservoir area. When a configuration number of five is used, the stand-alone systems (*Systems 2 & 4*) capture 1.04 $MtCO_2$ per year, while *Systems 1 & 3* capture 4.6 $MtCO_2$ per year using 282 MW_e of externally-supplied power.

Table 4: Capture Rates at 140°C Resource Temperature for varying Configuration Number

Configuration Number, N	Reservoir Area [km^2]	CO_2 Capture Rate (*Systems 2 & 4*) [$MtCO_2$/yr]	CO_2 Capture Rate (*Systems 1 & 3*) [$MtCO_2$/yr]	External Power (*Systems 1 & 3*) [MW_e]
1	1	0.04	0.19	11.3
2	4	0.17	0.74	45.1
3	9	0.37	1.66	101
4	16	0.66	2.96	180
5	25	1.04	4.63	282

4. CONCLUSIONS

Our work on the coupling of low-grade sedimentary geothermal and Direct Air Capture of CO_2 (geo-DAC), allows us to draw the following conclusions:

- A single 5-spot coupled geothermal plant and Direct Air Capture unit can capture up to 0.04 $MtCO_2$ per year (*System 2*) operating as a power island (i.e. no external power is exchanged). A plant of this size could capture 1.2 $MtCO_2$ over a 30 year lifetime.
- If external power is supplied with a 140°C resource, a single 5-spot geothermal plant with Direct Air Capture can capture up to 0.18 $MtCO_2$ per year or 5.4 $MtCO_2$ over a 30 year lifetime (*System 3*). The external power required in this configuration is 11.2 MW_e.
- If the single 5-spot systems are up-scaled to a 25 km^2 reservoir system, for a 140°C resource, the power island systems can capture 1.04 $MtCO_2$ per year while the externally-powered systems can capture 4.63 $MtCO_2$ per year using 282 MW_e. This 25 km^2 reservoir configuration is likely to minimize costs by sharing production wells between 5-spot reservoirs, as has been previously shown (Bielicki et al., 2016).
- With the current assumption of an adsorption-based DAC process whose heat demand is provided through saturated steam at atmospheric pressure, a resource temperature of 110°C generates the correct proportions of heat and electricity for the Direct Air Capture unit.
- The configurations which have an ORC parallel to the DAC (*System 2*) and serially as a topping cycle to the DAC (*System 4*) do not provide substantial differences in power generated or CO_2 captured.

5. ACKNOWLEDGEMENTS

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