Enter: Session: 02 - Technology Systems and Strategy for the Energy Transition

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Solid Sorbent Direct Air Capture Using Geothermal Energy Resources (S-DAC-GT) - Model for Region Specific Economic Analysis

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Abstract

Low temperature geothermal resources, ranging from 80° to 120°C, may substantially lower both the cost and the CO_2 emissions footprint of CO_2 direct air capture (DAC) systems. This paper provides a model for determining a region-specific economic analysis for DAC with solid sorbent (S-DAC) using geothermal resources (S-DAC-GT).

This paper provides a model for calculating estimated cost and carbon emissions for potential S-DAC facilities on a region-specific basis. The paper outlines the necessary region-specific characteristics required as parameters for the techno-economic model. The region-specific characteristics are then applied to an S-DAC energy and cost model based on existing literature to calculate the levelized cost per tonne of CO_2 captured and stored. Further, the model provides a reasonable approximation of the carbon intensity of the S-DAC-GT system. These calculations allow selecting and prioritizing regions appropriate for potential S-DAC-GT facilities operating at a scale of ~1 Mt CO_2 captured and stored per year.

Existing DAC techno-economic analyses are region agnostic and do not account for geothermal energy as the primary thermal energy source. The novelty of this paper is its deeper technical and economic analysis using geothermal energy as the thermal resource for the S-DAC process. This paper provides a model for customization of the techno-economic model specific to the target region. Further, the paper provides a consistent methodology for differentiating S-DAC-GT costs and carbon intensity by region.

Introduction

DAC is anticipated to play an essential role in a net zero carbon emissions future. This technology captures ambient atmospheric CO_2 independent of the source of emissions, allowing capture and storage of hard to avoid emissions from sources such as agriculture, forestry, and land use (18.4% of total emissions), transportation (16.2% of total emissions), especially aviation (1.9%), and heavy industry (i.e., iron-steel at 7.2% and cement at 3%) (Ritchie et al., 2020) not located close to geological formations suitable for storage. Not only does DAC mitigate these emissions, but large global deployment of DAC would reverse past emissions, important given that limiting global temperature rises to 1.5°C is no longer perceived as viable (UN News, 2022) due to the ongoing pace of CO_2 emissions.

The IEA, in its Net Zero Emissions by 2050 Scenario (IEA, 2021), anticipates DAC technologies to capture more than 85 Mt CO_2 per year by 2030, increasing to 980 Mt/year by 2050. This requires heroic acceleration of the adaption of the technology. Currently there are 18 small-scale facilities globally, operating in Canada, the EU, and the US (IEA, 2022). Combined, these facilities capture only ~8 kt CO_2 per year. The first large-scale DAC with a capacity of 1 Mt CO_2 per year is expected to begin operations in West Texas by the mid-2020's (Oxy, 2022). Increasing DAC capacity by four orders of magnitude by the end of this decade, and then by another order of magnitude within the following 20 years, will be an immense technological and economical challenge.

Compared to other methods of capturing CO_2, DAC is the most expensive due to the low concentration of CO_2 in the atmosphere (0.04%) versus flue gas from a power plant (3-14%) or a cement plant (14-33%) (Wang & Song, 2020). Therefore, basic thermodynamics dictates that DAC requires substantially more energy to capture the same amount of CO_2 than from flue gas. The IEA anticipates that the cost of DAC could approach $100 per tonne by 2030, but this will require massive investment in scale, technology, and innovation (IEA, 2022). The cost of DAC depends on several factors, including the technology used, the cost of heat and electricity, and factors related to the plant design and economics.

There are two major DAC technologies used today – liquid solvent-based DAC (L-DAC) and solid adsorbent-based DAC (S-DAC). There are other solutions that use electrochemical processes, ion-exchange resins, "nano-factories" based on molecular filters, and more, but this group remains experimental with little literature regarding their costs and commercial viability (Fasihi et al., 2019). S-DAC needs relatively low temperatures (~100°C) to release captured CO_2, while L-DAC needs very high temperatures, up to 900°C, to do the same. S-DAC can work with renewable energy sources, such as heat pumps and geothermal, but L-DAC typically relies on combusted natural gas to attain the high temperatures required for regeneration. If S-DAC were to utilize direct heat from geothermal wells (S-DAC-GT), it could potentially achieve the billion-tonne scale required to meet IEA goals. For example, there are many places in the world where brines with temperatures of 80–120°C can be produced with the existing oil and gas technologies. S-DAC adsorption happens at ambient temperature and pressure, while the desorption happens at low pressure and temperatures of ∼100°C. Currently, geothermal resources with brines at 80–120°C are underutilized, as they are inefficient for power generation. The process of turning thermal energy into electrical power has an average global efficiency of 12%, which means that most of the geothermal energy brought to surface is wasted during the process (Kuru et al., 2023; Livescu & Dindoruk, 2022). Using these low-temperature geothermal resources for direct heat applications, such as S-DAC, instead of for power generation, would increase their value while lowering S-DAC costs.

This paper presents a model to estimate S-DAC-GT costs, with customizable economic variables and region-specific parameters. The authors previously produced a paper applying this methodology to four specific regions: three in North America, and the fourth in Europe (Kuru et al., 2023). A major deficiency of this prior analysis is its limited applicability to regions outside North America and Europe. The purpose of this paper is to apply the methodology from the previous paper to produce a customizable publicly available model available for other researchers to estimate the viability of S-DAC-GT projects in any region, enabling easier comparison of costs between geographies.

Literature Review

This paper's techno-economic model relies on high-quality prior literature. These include techno-economic analyses of DAC that model the cost and energy requirements for DAC deployed at scale. This paper also builds on low-temperature geothermal economic techno-economic analysis which provide cost and energy estimates for geothermal systems that extract thermal energy at ~100°C from sedimentary formations. Moreover, as the thermal energy required in S-DAC is sensitive to ambient temperature and humidity, this paper relies on prior modeling of solid sorbent effectiveness in different climates. Finally, this paper expands upon the author's prior work developing the initial S-DAC-GT techno-economic model for four specific regions (Kuru et al., 2023).

DAC Techno-Economic Analyses

Techno-Economic Assessment of CO_2 DAC Plants (Fasihi et al., 2019)

This paper provides a techno-economic analysis of DAC plants using different technologies. It provides a methodology for calculating a levelized cost of DAC (LCOD) based on a fixed charge factor, referred to as "capital recovery factor" in the paper. It starts with an overview of the various DAC technologies and the companies, including a technical overview of low-temperature S-DAC (Figure 1).

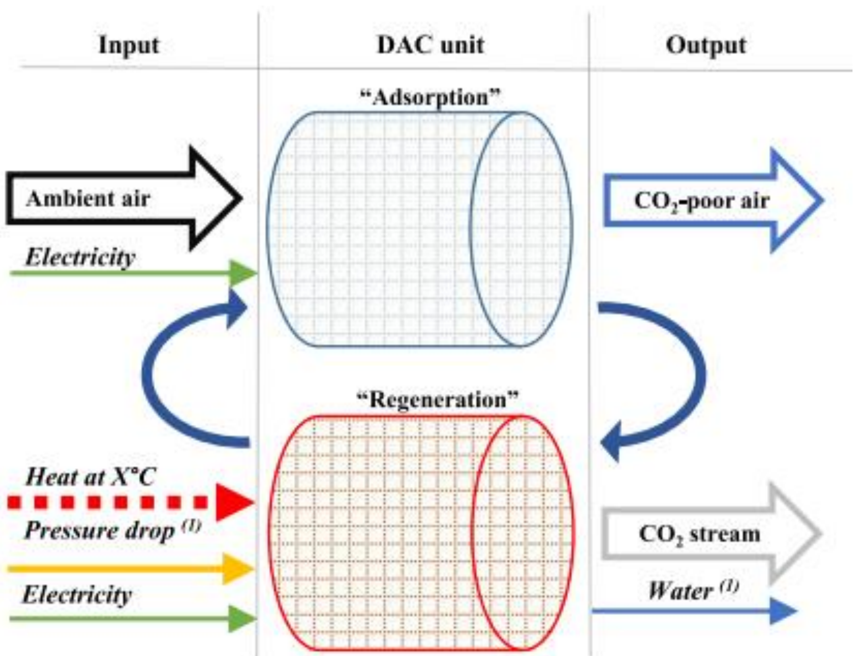

Figure 1 – S-DAC process (Fasihi et al., 2019).

Table 1 below, taken directly from Fasihi et al. (2019), provides the summary of the sources used to determine final L-DAC and S-DAC models. The models provide Capex, Opex, electrical and thermal energy values, which, after currency conversion and normalization for inflation, are input parameters for this paper's region-specific S-DAC model. The paper then determines likely LCOD estimates based on different thermal sources and electrical energy costs.

Table 1 – DAC model economics (Fasihi et al., 2019).

Economics of DAC as reported and recalculated.

technology	capacity	capex	opex	lifetime	el. demand	el. price	heat/fuel demand	indicated time of cost	cost reported	cost recalculated	type of source [a]	reference
	t_{CO2}/a	€/$t_{CO2}\cdot a$	%	years	kWh_{el}/t	€/MWh_{el}	kWh_{th}/t	year	€/t_{CO2}	€/t_{CO2}		
HT aqueous solution	280 000	-	-	20	-	-	-	2005	376	-	O	Keith et al. (2006)
	1 000 000	-	-	-	-	60	-	-	258	-	O	Holmes and Keith (2012)
	1 000 000	1583 [b]	4 [d]	20	494	53	2250	2011	309 [b]	314	O	Socolow et al. (2011)
	1 000 000	2086 [c]	4 [d]	20	494	53	2250	2011	395 [c]	388		
	1 000 000	-	-	-	-	53	1840	2013	283-300 [e]	-	O	Mazzotti et al. (2013)
	-	-	-	-	1500	-	0	large-scale	75-113 [f]	-	O	Carbon Engineering (2018c)
	1 000 000	1032 [k]	3.7	25	0	-	2450	2018	151, 209 [j]	200	O	Keith et al. (2018)
	1 000 000	714 [k, l]	3.8	25	0	-	2450	2018	114, 153 [j]	158		(Carbon Engineering)
	1 000 000	625 [k, l]	3.7	25	366	27-54	1460	2018	110-112, 137-147 [j]	139		
	1 000 000	549 [k, l]	3.8	25	77	27-54	1460	2018	85-87, 115-117 [j]	115		
	1 000 000	**815** [k]	**3.7**	**25**	**1535**	50	**0**	**2020**	-	186		**final model (this study)**
LT solid sorbent	3600	1220	-	25	694	-	2083	2015	-	244, 203 [g]	O	Roestenberg (2015)
	360 000	730	-	25	694	-	2083	2015	-	177, 135 [g]		(Antecy)
	-	-	-	-	150-260	-	1170-1410	first plant	<113	-	O	Kintisch (2014); Ping et al.
	-	-	-	-	150-260	-	1170-1410	n/a	11-38	-		(2018a; 2018b) (Global Thermostat)
	300	-	-	20	200-300	-	1500-2000	2014	-	-	O	Climeworks (2018b)
	-	-	-	-	-	-	-	large-scale	75	-		
	360 000	**730**	**4**	**20**	**250**	-	**1750**	**2020**	-	155, 120 [g]	-	**final model (this study)**

Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (National Academies of Sciences, 2019)

This paper by the National Academies of Science, Engineering, and Medicine (NAS) has a chapter dedicated to DAC, providing an overview of companies and technologies, while developing techno-economic models that generate a range of potential costs. The paper includes a carbon footprint analysis of the different DAC technologies, with different assumptions on energy sources and costs. It provides models for both L-DAC and S-DAC, using a range of potential input parameters, scaled from 1 to 5, calculating a range of likely costs. As a result, the paper produces a very wide range of potential outcomes for DAC costs, presented in Table 2. With respect to S-DAC, the middle range of estimated DAC costs (scenarios 2, 3, and 4) vary from $89 to $877 per tonne CO_2. The middle scenario provides an estimated cost of Capex of $133 per tonne CO_2 after the fixed charge factor is applied. Reversing this, using the paper's fixed charge factor of 12%, produces a Capex of $1,106 per tonne CO_2 capture capacity. Opex is estimated at $14.6 per tonne CO_2. The average of the scenario estimates 0.84 GJ electrical and 4.1 GJ thermal energy required per tonne CO_2 captured, or 232 kWh_e and 1,139 kWh_{th}.

Table 2 –DAC model economics (National Academies of Sciences, 2019).

Direct Air Capture System	Energy Source		Energy Required ($GJ/t\ CO_2$)		CO_2 Generated ($Mt/y\ CO_2$)		Net CO_2 Avoided	Capture Cost ($\$/t\ CO_2$)	
	Electric	Thermal	Electric	Thermal	Electric	Thermal	($Mt/y\ CO_2$)	Cap-tured	Net Re-moved[a]
Liquid Solvent	NG	NG	0.74-1.7	7.7-10.7	0.11-0.23	0.47-0.66	0.11-0.42	147-264	199-357
	coal	NG	0.74-1.7	7.7-10.7	0.18-0.38	0.47-0.66	0-0.35	147-264	233-419
	wind	NG	0.74-1.7	7.7-10.7	0.004-0.009	0.47-0.66	0.34-0.53	141-265	156-293
	solar	NG	0.74-1.7	7.7-10.7	0.01-0.03	0.47-0.66	0.31-0.52	145-265	165-294
	nuclear	NG	0.74-1.7	7.7-10.7	0.01-0.02	0.47-0.66	0.32-0.52	154-279	173-310
	solar	H2[b]	11.6-19.8	7.7-10.7	0.01-0.03	0	0.99	317-501	320-506
Solid Sorbent[c]	solar	solar	0.55-1.1	3.4-4.8	0.0004-0.008	0.008-0.01	0.892-0.992	88-228	89-256
	nuclear	nuclear	0.55-1.1	3.4-4.8	0.002-0.004	0.004-0.005	0.91-0.994	88-228	89-250
	solar	NG	0.55-1.1	3.4-4.8	0.0004-0.008	0.22-0.30	0.70-0.78	88-228	113-326
	wind	NG	0.55-1.1	3.4-4.8	0.002-0.003	0.22-0.30	0.70-0.78	88-228	113-326
	NG	NG	0.55-1.1	3.4-4.8	0.07-0.14	0.22-0.30	0.56-0.71	88-228	124-407
	coal	coal	0.55-1.1	3.4-4.8	0.15-0.3	0.32-0.44	0.26-0.53	88-228	166-877

[a] Assuming the use of an oxy-fired kiln to provide heat from natural gas in the calcination process, leading to greater CO_2 production and hence lower cost of net CO_2 removal, using a basis of 1.3 Mt CO_2 for NG/NG, 1.2 Mt CO_2 for coal/NG. (NG = natural gas).

[b] Assuming all hydrogen is produced via electrolysis using near zero-carbon power.

[c] Scenarios range from 2-low to 4-high.

Direct Air Capture Case Studies: Sorbent System by the NETL (Valentine et al., 2022)

This 2022 analysis by the National Energy Technology Laboratory (NETL) builds substantially on the prior NAS (2019) techno-economic analysis. The paper evaluates sorbent-based DAC models, comparing packed bed versus monolith sorbent configurations, and assumes CO_2 emissions-free electricity. The monolith sorbent configuration is most comparable to current commercial S-DAC designs. The paper's model improves on the NAS (2019) analysis by integrating new literature on sorbent characteristics. The updated model estimates Capex of $1,909 per tonne CO_2 capture capacity, and Opex of $115 per tonne CO_2. It assumes 100% electrical sources, but by backing out energy required for the electric boiler, the required electrical and thermal energy can be determined at 2,268 kWh_e and 1,453 kWh_{th}, respectively, per tonne CO_2.

Summary of Techno-Economic Parameters

The three techno-economic models produce a wide range of S-DAC parameters. Table 3 includes a comparable summary of the parameters from the three techno-economic models. The model in this paper allows adjustment of these paraments based on the specific sorbent technology and configuration. The model is highly customizable, allowing comparison of costs based on specific technical and regional factors, and inclusion of proprietary cost and energy data.

Table 3 – Techno-economic model parameters summary.

$ per tonne CO_2	CAPEX**	OPEX	MW_e	MW_{th}
Fasihi et al. (2019)	935.02	37.40	0.25	1.75
NAS (2019)	1291.86	17.05	0.23	1.14
NETL (2022)	1909.00	115.00	2.27	1.45
Average	1378.63	56.48	0.92	1.45

** Normalized exchange rates (if applicable) and 2022 H1 inflation*

*** Per tonne of annual DAC capacity*

Low-Temperature Geothermal Techno-Economic Analysis

Low Temperature Geothermal Resource Assessment for Membrane Distillation Desalination in the US (Akar & Turchi, 2016)

Although this paper from the National Renewable Energy Laboratory (NREL) is focused on the economics of extracting low-temperature geothermal energy for desalination, its geothermal techno-economic model can be directly used for all low temperature applications. The paper uses estimated capital and operating costs to calculate the levelized cost of heat (LCOH) from new and existing geothermal wells, determined to be on the order of ~1¢ per kWh_{th} for new wells. Desalination requires lower temperatures than DAC, and the paper models a geothermal reservoir of 90°C at a depth of 1,250 m, or 4,101 ft. LCOH for DAC needs to be normalized to the depth of the target geothermal temperature of 120°C. Further, due to the large flow rates assumed in the paper's model (89 L/s) and highly customized requirements of the S-DAC facility, the model in our paper assumes only new wells, resulting in a higher, and more conservative, LCOH. Finally, the model is dated from 2016 and needs to be normalized for improved drilling efficiency and inflation.

For geothermal energy production, the paper assumes a production temperature of 90°C and reinjection at 55°C. DAC requires production at 120°C and reinjection at 80°C. The thermal energy produced by geothermal brine flow is calculated using equation (1).

$$Thermal\ energy\ (W) = \Delta T \cdot q \cdot C \cdot t \cdot r \tag{1}$$

$T = temperature$
$q = flow$
$C = heat\ capacity$
$t = time$
$r = Capacity\ utilization\ rate$

Due to incremental costs of deeper drilling and greater pumping pressures required for S-DAC, the normalized cost of LCOH for S-DAC can range from 1.8¢ to 4¢ per kWh_{th}, higher than the paper's estimated LCOH.

DAC Sensitivity to Local Climate

Optimal Design and Operation of Solid Sorbent DAC Processes at Varying Ambient Conditions (Wiegner et al., 2022)

This paper completes a thorough analysis of the impact of various factors on the efficiency of S-DAC processes. It observes that higher ambient temperatures or lower humidity results in higher energy consumption and lower CO_2 capture productivity, although the relation may be non-linear. The papers concludes colder and more humid regions have substantially lower thermal energy requirements for S-DAC. The relationship is best captured in the paper's Figure 5(b) "Normalized capturing costs and specific energy requirements at different ambient conditions", Figure 2 below.

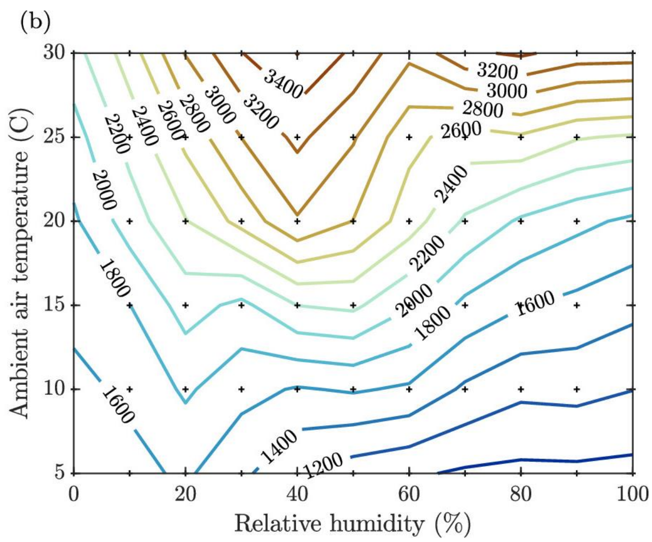

Figure 2 – kWh required per temperature and humidity (Wiegner et al., 2022).

NETL's (2022) techno-economic model assumes a facility in an environment with 60% humidity and 15°C, requiring 2,000 kWh_{th} per Figure 2. In this paper's model, this baseline is assumed to have DAC Thermal Energy Multiplier of 1.0 (see Regional Parameters section). Regional climate conditions can be incorporated into the model using this multiplier. For example, a region averaging 50% humidity and 20°C would require 2,800 kWh_{th} based on Figure 2. Therefore, its multiplier would be 2800/2000, or 1.4.

Region Specific Analysis

S-DAC-GT – Region Specific Analysis (Kuru et al., 2023)

The authors' prior techno-economic analysis for S-DAC-GT focused on four specific regions: 1. Houston area Texas Gulf Coast, 2. Los Angeles Basin in California, 3. Alaska's Cook Inlet, and 4. Netherlands' Groningen Gas Field.

These regions were selected primarily due to proximity to proven and accessible geothermal resources with temperatures on the order of 120°C, and due to proximity to high quality sedimentary basins for permanent geological storage of CO_2. The model applies i) the average S-DAC cost and energy parameters from the three techno-economic analyses, ii) geothermal LCOH normalized for depth of the geothermal reservoir, iii) region specific energy costs, iv) region specific Capex and Opex multipliers, and v) a thermal energy multiplier based on the average humidity and temperature of the region. The model also determines S-DAC CO_2 intensity based on the profile of the regional electrical power supply. Figure 3 shows the range of regional LCOD calculated for a 100% electric baseline system and S-DAC-GT systems using new and existing wells for geothermal energy. Figure 4 show the range of CO_2 intensity calculated for three different thermal energy sources for S-DAC: Baseline (100% electric), natural gas, and geothermal (S-DAC-GT).

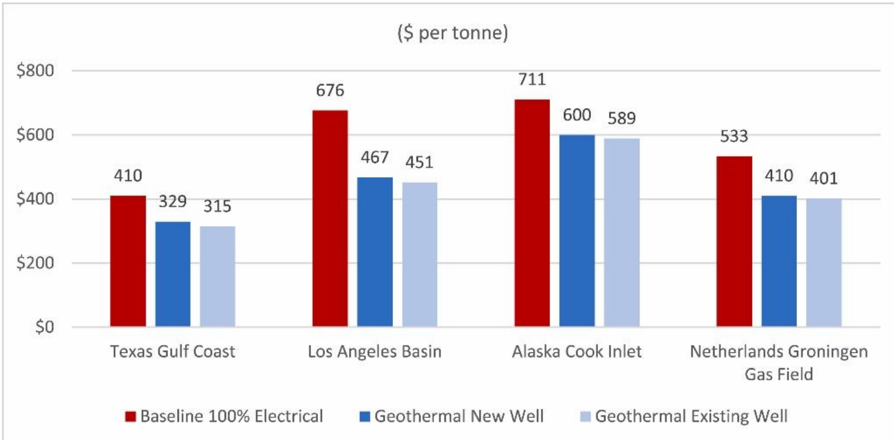

Figure 3 – Levelized Cost of DAC.

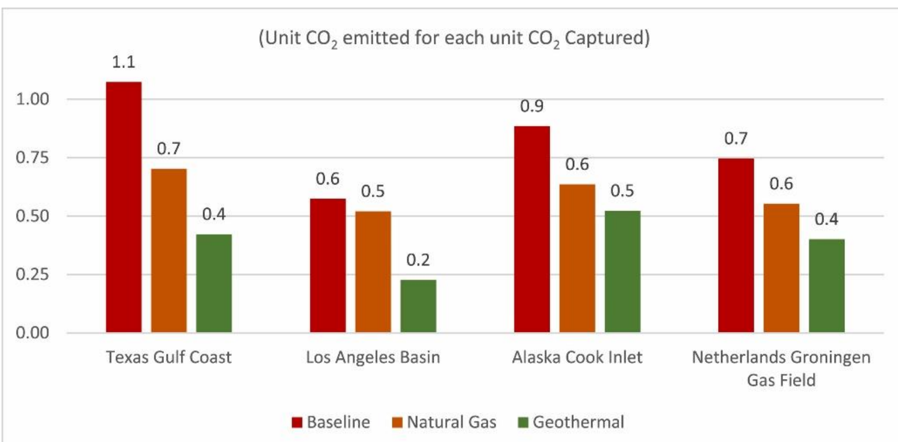

Figure 4 – CO_2 intensity.

Running the model on sample regions provides a spectrum of costs and carbon footprints. As DAC is a very energy intensive process, the model demonstrates that using a geothermal reservoir for thermal energy can reduce S-DAC costs by up to 33%. Further, regional costs of the S-DAC-GT system can vary by over 1.8X. Finally, upon running the model on different regions, it is observed that DAC CO_2 intensity is heavily influenced by the CO_2 footprint of the regional electricity supply – the regions sampled had DAC carbon intensities ranging from under ¼ unit of CO_2 emitted per unit captured, to greater than ½, even when utilizing geothermal resources for thermal energy. These regional variations of costs and carbon intensities emphasize the importance of a rigorous process in site selection for any future large-scale S-DAC-GT facility.

The region-specific techno-economic analysis in Kuru et al. (2023) provides the basis of the customizable model in this paper. The calculated values in the prior paper are fixed for the economic conditions of the region and the time period. The goal of this newer paper is a model that provides flexibility in determining capital cost parameters, DAC process cost and energy parameters, and region-specific parameters. The resulting model provides a tool for appropriately comparing potential regions to ensure optimal site selection.

Model Description

The techno-economic model combines economic, technical, and regional parameters to determine levelized cost of DAC (LCOD) and the CO_2 intensity of DAC. CO_2 intensity is defined as the units of CO_2 emitted per unit of CO_2 captured via DAC. LCOD and CO_2 intensity are calculated for three different scenarios:

1) 100% electrical system: heat for S-DAC is generated using electricity
2) Natural gas: heat for S-DAC is generated burning natural gas
3) S-DAC-GT or geothermal: heat for S-DAC is generated from geothermal resources

The final model Python code for execution can be found at: https://github.com/kurutim/SPE-215735-MS.git

Input Parameters

Economic Parameters

Economic parameters determine the capital cost required to calculate the levelized cost of DAC (LDAC). The two inputs are:

WACC	Weighted average cost of capital.
Number of Years (N)	Expected lifetime of the facility in years, over which the capital costs of the project may be amortized.

The default values used in the model are 10% for WACC and 20 years for N. These can be customized based on the specific requirements of the DAC project.

WACC and N are used to calculate the Fixed Charge Factor (FCF) in equation (2).

$$FCF = WACC \cdot \frac{(1 + WACC)^N}{(1 + WACC)^N - 1} \tag{2}$$

The FCF is used to amortize the capital costs of the project (Capex), used to calculate determine LCOD. The data entry window for the economic parameters is shown in Figure 5.

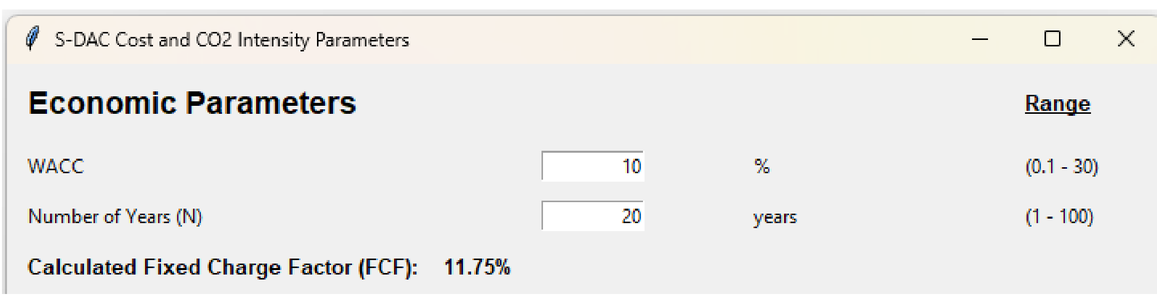

Figure 5 – Economic parameters input window.

DAC Technical Cost and Energy Parameters

The DAC process requires four input parameters. The default values are the averages calculated from the three DAC techno-economic models discussed in the Literature Review section.

Capex	The estimated capital cost in USD of the DAC facility, per annual tonne of CO_2 capture capacity. The default value is \$1,379 per tonne of CO_2 annual capture capacity.
Opex	The estimated operating cost in USD of the DAC facility, per tonne of CO_2. This excludes the cost of electrical and thermal energy. The default value is \$56 per tonne CO_2.
Electrical Energy	The estimated electrical power consumption in kWh_e per tonne of CO_2. The default value is 916 kWh_e per tonne of CO_2.
Thermal Energy	The estimated thermal power consumption in kWh_{th} per tonne of CO_2. The default value is 1,447 kWh_{th} per tonne of CO_2.

These values are required to calculate levelized cost of DAC (LCOD) presented in equation (3).

$$LCOD = Capex_{DAC} \cdot CRF + Opex + DAC_{electrical\ energy} \cdot LCOE + DAC_{thermal\ energy} \cdot LCOH \qquad (3)$$

LCOD requires levelized cost of electricity (LCOE) and levelized cost of heating (LCOH). These are determined from regional parameters covered below.

The portion of the data entry window for DAC technical cost and energy parameters is in Figure 6.

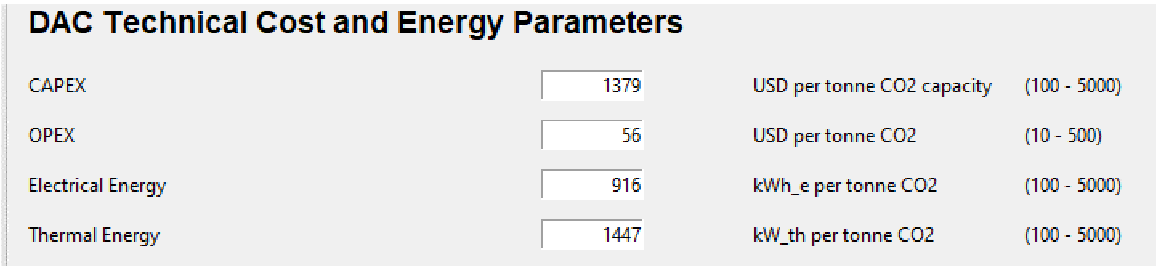

Figure 6 – DAC cost and energy parameters input window.

Regional Parameters

LCOE and LCOH are determined regionally. Regions have variable electric power sources, which determine CO_2 emissions due to DAC. Further, different regions have different economies, resulting in different relative capital and operating costs. Finally, regional climates, average temperature and humidity, can impact S-DAC process efficiency, requiring different amounts of thermal energy. Regional parameters determine the final calculated LCOD and CO_2 intensity of the planned DAC facility. The parameters are:

Natural Gas Price

Price of natural gas in USD per Mcf. This is used to determine the LCOD scenario using natural gas as the thermal energy source. The default value is $5, but this can change dramatically between regions, and should be based on expected future prices.

Electricity Price

Price of regional industrial electricity in USD per kWh. The default value is $0.15.

CO_2 Intensity of Electricity

The estimated CO_2 emissions per MW_e. This is dependent on the profile of fuel sources for the electricity used within the region. This can be as high as 1 tonne CO_2 per MWh if the source is coal. The average for the US in 2021 was 0.40, which is the default.

Capex Multiplier

The estimated cost of capital projects within the region, relative to the US average. The default is 1.0.

Opex Multiplier

The estimated cost of operating costs within the region, relative to the US average. A good proxy is relative regional costs of living. The default is 1.0.

S-DAC Thermal Energy Multiplier

The thermal energy required for S-DAC is highly dependent on ambient temperature and humidity. This multiplier is covered in the Literature Review section, under the Optimal Design and Operation of S-DAC Processes at Varying Ambient Conditions subsection. Cooler and more humid regions require lower thermal energy for S-DAC. The default value is 1.0

Geothermal Reservoir Depth

The depth of the geothermal reservoir has a large impact on geothermal LCOH. Drilling depth drives the cost of injection and production wells, and pump operating costs. The depth is in feet and measured from surface to the depth where bottom hole temperature is at least 120°C. This depth can vary substantially between regions. The default value is 10,000 ft.

Geothermal Reservoir Temperature Drawdown

Thermal drawdown, or cooling, of the geothermal reservoir can happen very quickly, but will level out asymptotically, approaching a stable temperature. This can be difficult to model, and the decline in temperature is highly dependent on well design and reservoir engineering, as well as reservoir properties. The model anticipates geothermal brine is initially extracted at 120°C and reinjected at 80°C. The default drawdown value is 10°C, implying the long-term geothermal brine temperature is 110°C.

CO_2 Transport — Transportation cost of the captured CO_2 to the permanent geological storage reservoir. This is dependent on the proximity to the injection reservoir and the regional CO_2 pipeline infrastructure. The default is $10 per tonne CO_2.

CO_2 Storage — Cost of injection and storage of CO_2 into the permanent geological storage reservoir. This is dependent on depth, size, and quality of the CO_2 storage reservoir. This is highly dependent on regional geology. The default is $10 per tonne CO_2.

The portion of the data entry window for regional parameters is in Figure 7.

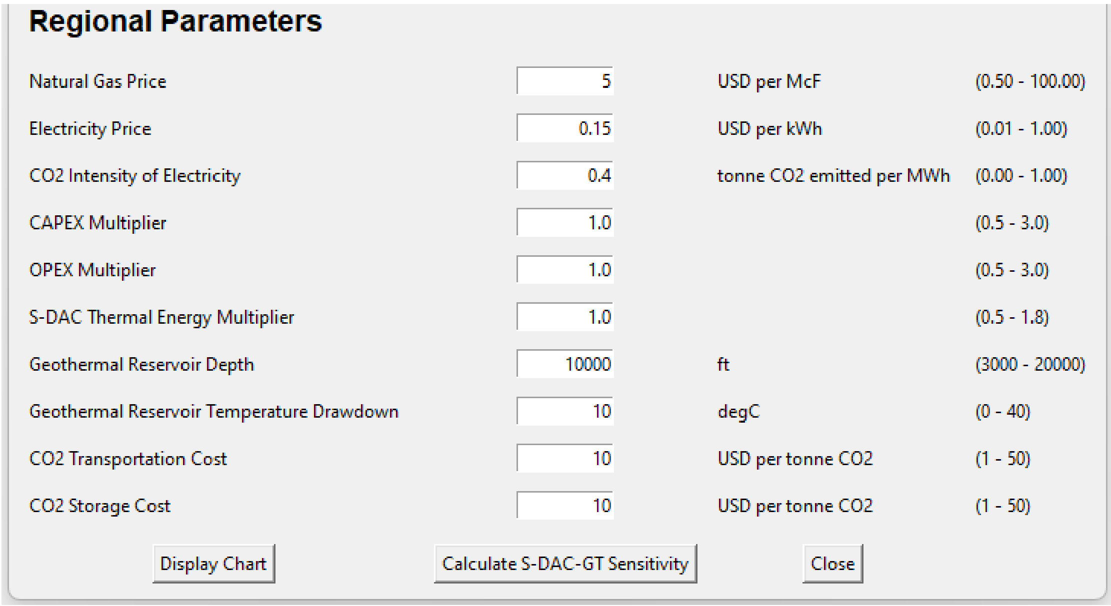

Figure 7 – Regional parameters input window.

Once the input parameters are entered, “Display Chart” can be selected to display the results.

Model Outputs

The model calculates LCOD and the CO_2 intensity for the three thermal energy source scenarios. The final model output includes CO_2 transport and storage costs, as in equation (4).

$$LCOD_{final} = LCOD(eq\ 2) + CO_2Transport + CO_2Storage \quad (4)$$

A total of six values are calculated:

$LCOD_{final}$ — Regional LCOD in USD for S-DAC scenarios using thermal energy from electricity, natural gas, and geothermal resources.

CO_2 Intensity — Regional CO_2 intensity for the S-DAC process using thermal energy from electricity, natural gas, and geothermal resources.

The output is consolidated into two bar graphs displayed after the user enters all required data. An example is in Figure 8, showing the results of the model run with the default values. This is a reasonable approximation of a generic S-DAC-GT plant within the US, assuming nearby geothermal and CO_2 storage resources.

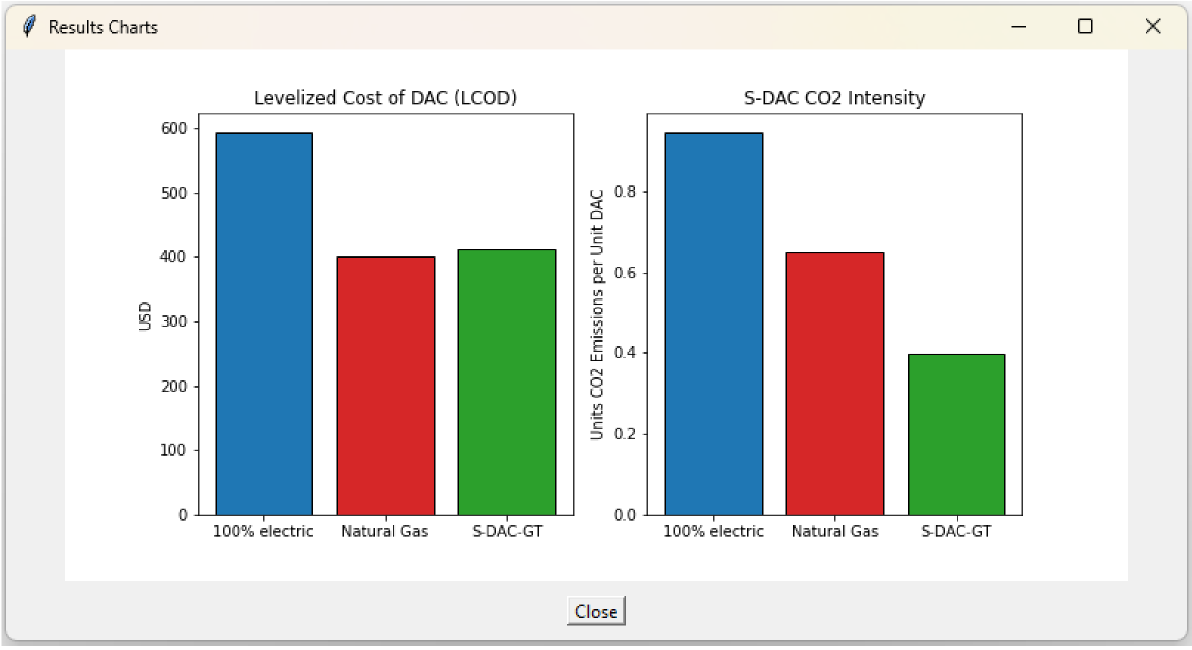

Figure 8 – Model LCOD and CO_2 intensity output window.

Sensitivity Analysis

The model also includes a fast way for the user to conduct a sensitivity analysis, given custom parameters. Once the user has entered their DAC cost and energy parameters and region-specific parameters, they can execute a sensitivity calculation for all the parameters. The model allows the user to enter a custom "delta" value. In other words, the model is executed with each parameter sequentially adjusted by ± delta, and the results tabulated for both change in LCOD and CO_2 intensity. The default delta value is 25%, but the user may run the model for multiple values to see the impact of different magnitude of changes. The sensitivity analysis is only applied to the S-DAC-GT model, not the baseline 100% electric nor the natural gas scenarios. The sensitivity analysis window is presented in Figure 9.

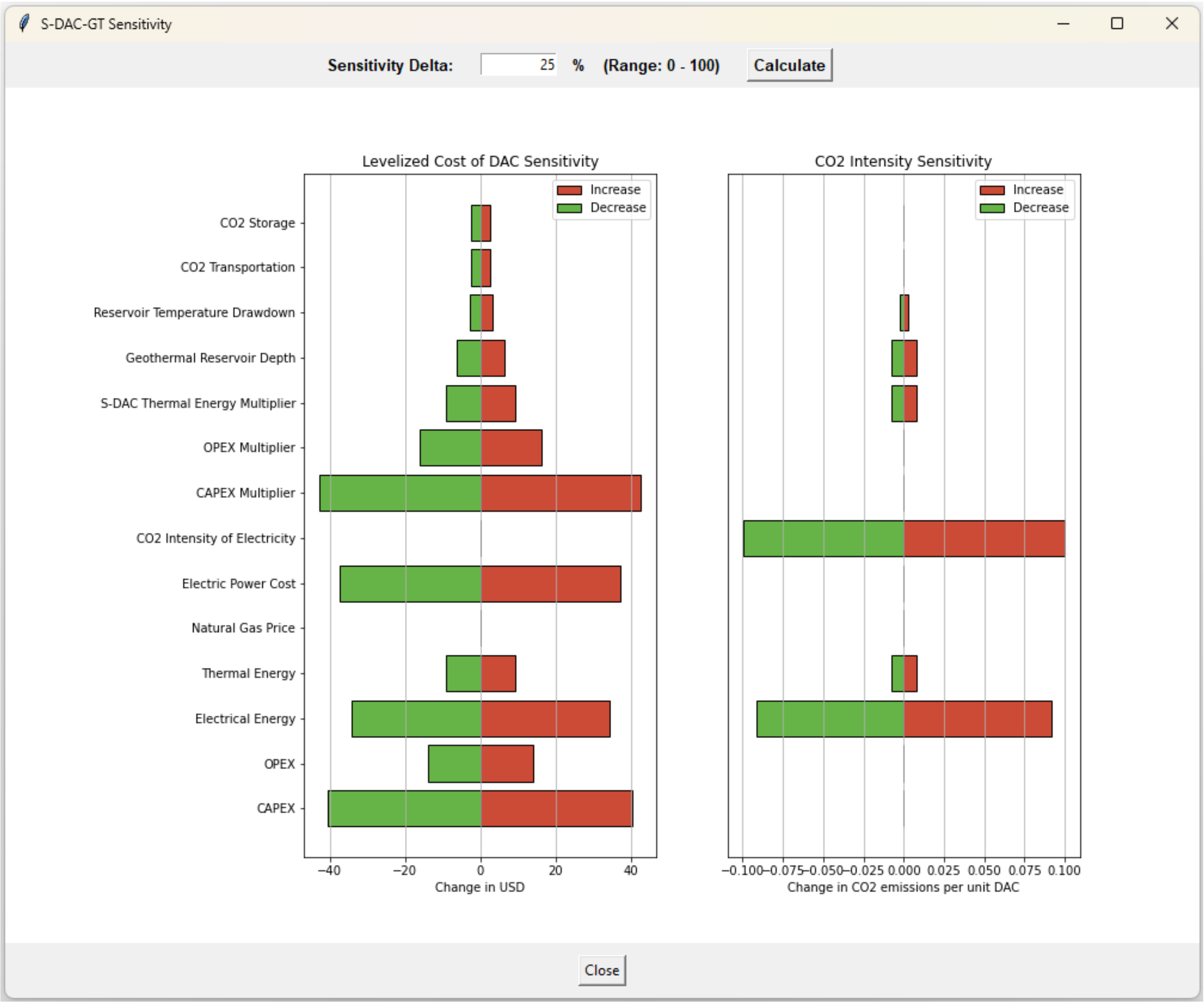

Figure 9 – S-DAC-GT sensitivity calculation window.

Future Studies

Low temperature and low-cost geothermal energy can substantially lower the cost and CO_2 intensity of S-DAC. There remains considerable scope to continue research in this space, building upon the methodology of this paper. Three possible areas of follow-on research are:

1) **Techno-economic review of S-DAC-GT with permanent storage of CO_2 via mineralization.** This model has focused on CO_2 storage in sedimentary formations such as depleted oil and gas fields or aquifers. Storage of CO_2 via mineralization in mafic and ultramafic formations is a growing field of experimentation and research. Such formations are more likely to coincide with higher thermal gradients and access to shallower and hotter geothermal reservoirs. More accessible geothermal energy may offset the potential greater cost of CO_2 storage via mineralization.

2) **Reservoir modeling of low temperature geothermal resources in sedimentary formations**. As mentioned above, the thermal drawdown of the formation can have a significant effect on S-DAC-GT efficiency. An area of further study could be enabling faster modeling of potential reservoirs to establish the likely thermal drawdown and suitability for an S-DAC-GT project.

3) **Techno-economic review of smaller scale S-DAC-GT projects using existing oil and gas wells.** An assumption of this paper is the geothermal reservoir requires new customized injection and production wells to provide large flow volumes of hot brine necessary to support a ~1 Mt S-DAC facility. In contrast, smaller modular S-DAC systems may allow lower-cost deployment of S-DAC to a huge number of existing wells connected to depleted oil and gas fields with high bottom hole

temperatures. Elimination of the cost of drilling and completing new wells would substantially reduce geothermal LCOH. However, this solution would be constrained by the quantity of thermal energy the pre-existing wells could provide an S-DAC facility.

Conclusions

The conclusions of this paper are five-fold:

1) The default parameters represent a reasonable approximation of the likely costs of a relatively high-quality S-DAC-GT facility. These suggest that geothermal energy will likely reduce S-DAC costs by approximately a third, and possibly more with rigorous site selection.
2) Although using natural gas for thermal energy may produce LCOD savings on par with cost reductions due to geothermal energy, CO_2 emissions from the combusted CH_4 would result in substantially higher CO_2 intensity that an S-DAC-GT facility.
3) Sensitivity analysis of typical parameter values indicates that the largest cost drivers of S-DAC-GT are Capex and electricity prices. The relative weight of Capex costs shows the value of continued innovation in DAC technology, and the importance of cost reduction through economies of scale. The impact of the cost of electricity reflects the energy intensity of DAC, and the importance of low-cost electricity even if thermal energy is proved by cheaper geothermal resources.
4) A "clean" electricity grid is essential for DAC to be an efficient CO_2 emissions mitigation solution. Even using geothermal energy, the average electricity profile within the US results in close to 0.4 units of CO_2 emissions per unit of CO_2 captured via S-DAC-GT. Without a near zero-emissions electricity supply, DAC remains an impractical climate mitigation solution.
5) The customizable model provided by this paper provides a region agnostic tool to evaluate and compare potential S-DAC-GT solutions throughout the world. Such a tool is a critical first-pass filter in evaluating the viability of any global S-DAC-GT project. An example of how it could be used to compare regions for S-DAC-GT deployment is shown in Figure 10 and Figure 11. These figures compare the output of the default parameter values with the four regions evaluated in the prior paper by the authors (Kuru et al., 2023).

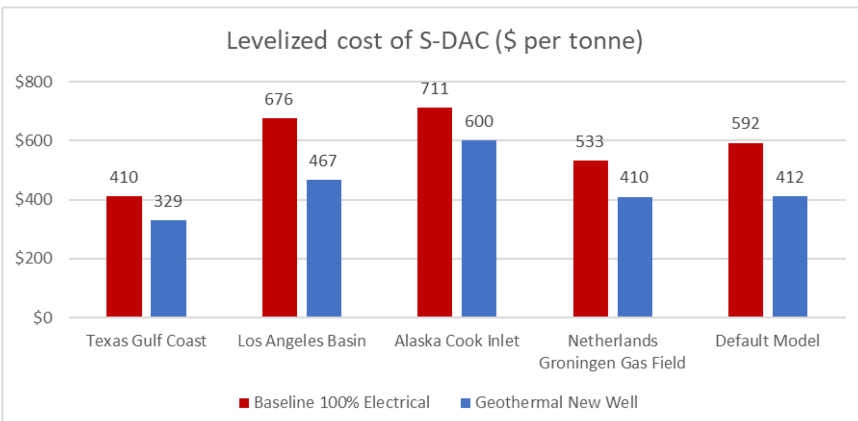

Figure 10 – Regional LCOD comparison.

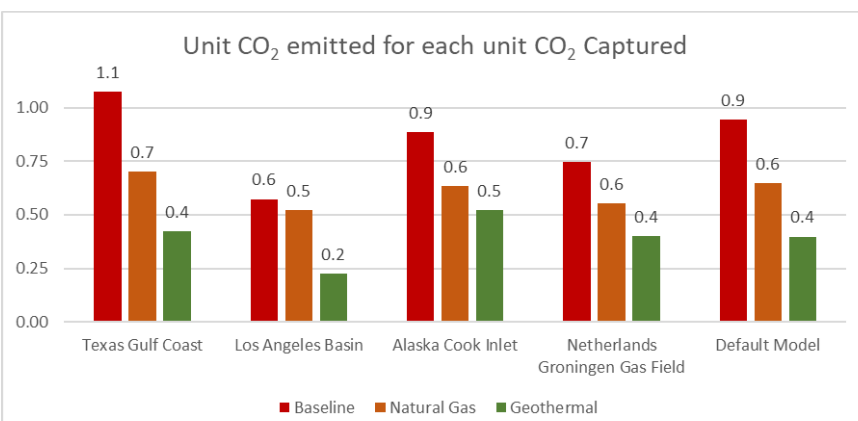

Figure 11 – Regional CO2 Intensity comparison.

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