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The Water, Energy, and Carbon Dioxide Sequestration Simulation Model (WECSsim™): A User's Manual

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The Water, Energy, and Carbon Dioxide Sequestration Simulation Model (WECSsim™): A User's Manual

Peter H. Kobos[1], Jesse D. Roach[1], Geoffrey T. Klise[1], Jason E. Heath[2], Thomas A. Dewers[2], Karen A. Gutierrez[3], Leonard A. Malczynski[1], David J. Borns[3] and Andrea McNemar[4]

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Abstract

The Water, Energy, and Carbon Sequestration Simulation Model (WECSsim) is a national dynamic simulation model that calculates and assesses capturing, transporting, and storing CO_2 in deep saline formations from all coal and natural gas-fired power plants in the U.S. An overarching capability of WECSsim is to also account for simultaneous CO_2 injection and water extraction within the same geological saline formation. Extracting, treating, and using these saline waters to cool the power plant is one way to develop more value from using saline formations as CO_2 storage locations.

WECSsim allows for both one-to-one comparisons of a single power plant to a single saline formation along with the ability to develop a national CO_2 storage supply curve and related national assessments for these formations. This report summarizes the scope, structure, and methodology of WECSsim along with a few key results. Developing WECSsim from a small scoping study to the full national-scale modeling effort took approximately 5 years. This report represents the culmination of that effort.

The key findings from the WECSsim model indicate the U.S. has several decades' worth of storage for CO_2 in saline formations when managed appropriately. Competition for subsurface storage capacity, intrastate flows of CO_2 and water, and a supportive regulatory environment all

play a key role as to the performance and cost profile across the range from a single power plant to all coal and natural gas-based plants' ability to store CO_2. The overall system's cost to capture, transport, and store CO_2 for the national assessment range from $74 to $208 / tonne stored ($96 to 272 / tonne avoided) for the first 25 to 50% of the 1126 power plants to between $1,585 to well beyond $2,000 / tonne stored ($2,040 to well beyond $2,000 / tonne avoided) for the remaining 75 to 100% of the plants. The latter range, while extremely large, includes all natural gas power plants in the U.S., many of which have an extremely low capacity factor and therefore relatively high system's cost to capture and store CO_2.

For context, the first gigatonne of CO_2 captured from all coal and natural gas power plants has a cost of only $61 / tonne of CO_2 stored and $85 / tonne avoided. These levels correspond to approximately 7,626 million gallons per day (MGD) of added water demand for the avoided emissions, and for a storage rate of 1 $GtCO_2$ per year, this uses 5% of all capacity across the formations.

The analytical value and insight provided by WECSsim allow users to run power plant- and formation-specific scenarios to assess their cost and performance viability relative to other pairings throughout the lower 48 states of the U.S. Along with a national-level perspective, the results can identify which power plants are the most economically viable for CO_2 capture, transportation, and storage (CCS), and which saline water-bearing formations are the most likely candidates to support large-scale, multi-decade CCS. A wide suite of scenarios can be developed by adjusting the cost and engineering parameter assumptions throughout WECSsim. With this capability, interested parties can address questions regarding geologic parameters, power plant make-up power, water treatment costs, and efficiencies, amongst many other salient variables both at the power plant level, and when developing a nation-wide assessment.

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ACRONYMS AND ABBREVIATIONS

atm	atmosphere
AWWA	American Water Works Association
BC	Brine concentrator
BEG	Bureau of Economic Geology
Btu	British Thermal Unit
¢	cents of USD
C	centigrade
Cap	Capacity
CC	CO_2 capture(d)
CCC	CO_2 capture and compression
CCS	CO_2 capture, compression and storage (sequestration)
CO_2	carbon dioxide
CoP	ConocoPhillips Company
CS	CO_2 storage
D	density
da	day
EPA	Environmental Protection Agency
EPEC	Existing Plants, Emissions & Capture
EPRI	Electric Power Research Institute
FID	formation identification
ft	foot
Fm	formation
FV	Future Value
gal	gallon
gpm	gallons per minute
GEE	General Electric Energy
GWh	Gigawatt hour
H_2O	water
HERO	High Efficiency Reverse Osmosis
HHV	high heating value
hr	hour
ID	identification
IGCC	integrated gasification combined cycle
in	inch
IPCC	Intergovernmental Panel on Climate Change
km^2	kilometers squared
kW	kilowatt
kWh	kilowatt hours
lb	pound
LCOE	levelized cost of electricity
m	meter
max	maximum
mD	millidarcy
mi	mile

mid	midpoint
min	minimum
MIT	Massachusetts Institute of Technology
MGD	million gallons per day
MGSC	Midwest Geological Sequestration Consortium
MMBtu	Million Btu
Mmt	million metric tonnes
MRCSP	Midwest Regional Carbon Sequestration Partnership
Mt.	mount
MUP	make-up power
MWh	megawatt hour
N	North
n/a	not available
NatCarb	National Carbon Sequestration Database and Geographic Information System
NETL	National Energy Technology Laboratory
NGCC	natural gas combined cycle
O&M	operations and maintenance
Pa	pascal
PC	pulverized coal
PC-Sub	pulverized coal, subcritical
PC-Super	pulverized coal, supercritical
pdf	probability distribution function
PI	potentially intersecting
ppm	parts per million
ppt	parts per thousand
RO	reverse osmosis
s	second
SECARB	Southeast Regional Carbon Sequestration Partnership
st	Shell technologies
St.	Saint
SNL	Sandia National Laboratories
SS	sandstone
TDS	total dissolved solids
TP	temperature and pressure
U.S.	United States
USD	U.S. dollars
$	USD
U.S. GDP	United States gross domestic product
USAEE/IAEE	United States Association for Energy Economics / International Association for Energy Economics
Vbrine	volume of brine
Vco2	volume of CO_2
W	West
WECSsim	Water, Energy, and Carbon Sequestration Simulation Model
yr	year

1. AN INTRODUCTION TO THE WATER, ENERGY AND CARBON SEQUESTRATION MODEL (WECSsim)

1.1 Background

As the United States (U.S.) looks to manage carbon dioxide (CO_2) emissions from power generating facilities, storing the CO_2 in the subsurface may be a large-scale option. When storing CO_2 at the scales discussed to manage a large portion of the U.S.'s emissions it is necessary to evaluate the technical and economic feasibility of a proposed system. This type of analysis pulls in existing research and helps identify potential data gaps that need to be addressed to reduce the uncertainty in how much CO_2 could be stored and for what cost. Reducing this uncertainty helps define a range of costs that need to be evaluated against potential policy scenarios to determine if CO_2 capture, transportation, and storage (CCS) technology is ready for large-scale deployment.

An area of the subsurface that has great potential for CCS are deep saline formations due to a predominance of sedimentary rocks with abundant pore space in most locations in the U.S. These saline formations can potentially offer more pore space for storage if the existing water can be removed and replaced with CO_2. This is where the Water, Energy, and Carbon Sequestration Model (WECSsim) can be utilized. This model synthesizes the disciplines of geoengineering, geochemistry, energy systems engineering, energy economics, spatial analysis for well field assessment and formation evaluation through geographic information systems, and water treatment engineering. Utilizing these fields the WECSsim model seeks to:

- evaluate and catalog saline formations in the U.S. that may be amenable for storing CO_2,
- assess the cost to capture, compress, transport, and store CO_2 in the subsurface,
- assess the potential to treat and then use extracted water from saline formations for additional power plant cooling, and
- identify the lowest cost locations for simultaneous CCS and saline water extraction to maximize the potential storage volumes of CO_2.

1.2 Purpose of WECSsim

WECSsim is a dynamic simulation model incorporating the stocks and flows associated with potential CO_2 capture and sequestration systems (e.g., power plant's metrics, electricity production, flows of CO_2, water resource needs and treatment costs, etc.) and the economics associated with the system. This model provides interested parties with the ability to perform what-if scenario analyses in real time via an interactive interface. For example, the model can address questions such as: What if the level of CO_2 capture increases from 50% to 70%? What will the electricity costs look like due to this change? Similar scenario questions can be developed for different power plant configurations, geologic formations used for CO_2 storage, and brackish water pumping treatment technologies.

1.3 WECSsim Model Architecture and Scope

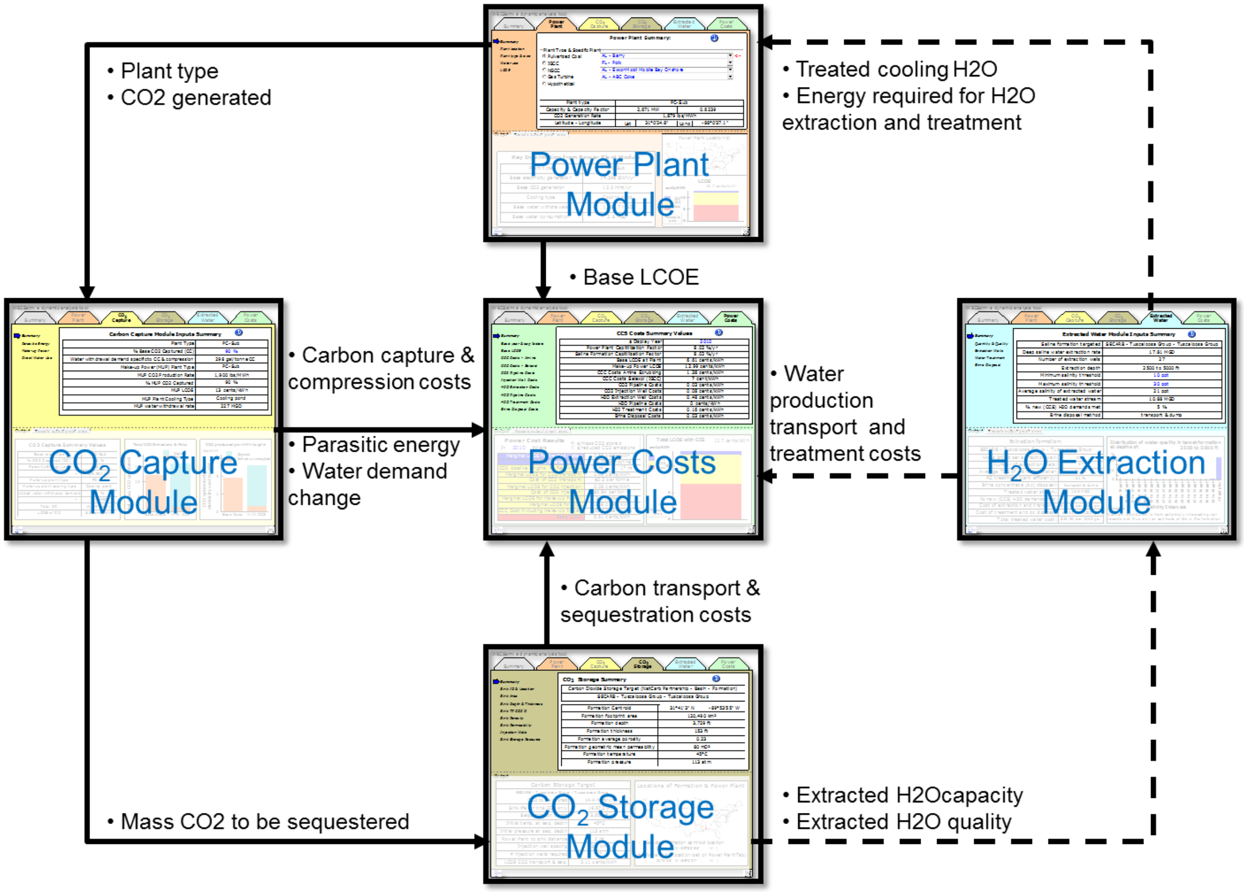

Figure 1. WECSsim schematic diagram.

Throughout this document, Figure 1 serves as the central key to WECSsim's structure and subsequent description. The document develops a series of sections and corresponding scenarios based on each of the five model modules illustrated in Figure 1. Additionally, Section 8 is devoted to the combination of all power plants and all potential CO_2 geologic sinks listed in WECSsim to give an overall U.S., national-level supply curve of storage volume and corresponding costs. Figures 2a, 2b, 2c and 2d illustrate the underlying structure's interface screens of WECSsim. Throughout this document, descriptions and corresponding model interface screens are illustrated for the modules shown in Figure 1. The highest level of the WECSsim user interface is organized in six 'tabs' representing the five modules shown in Figure 1 plus a summary tab.

1.4 Navigating WECSsim

WECSsim has several different levels of detail outlined in Figures 2a, 2b, 2c and 2d. The latter three correspond with the deeper levels of analysis used to assess the national-scale cost-, water-, and formation-use curves.

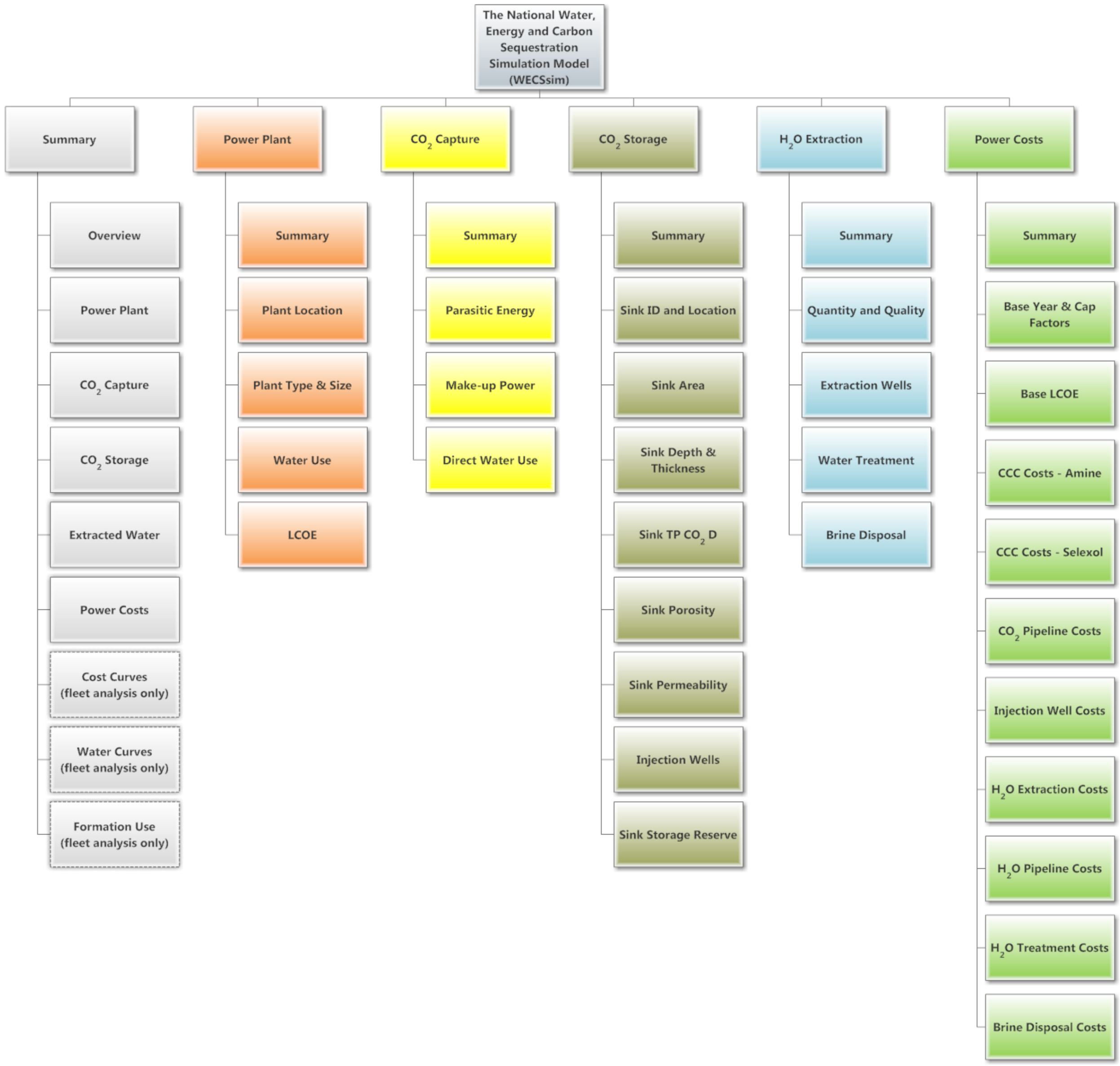

Figure 2a. WECSsim interface menu map.

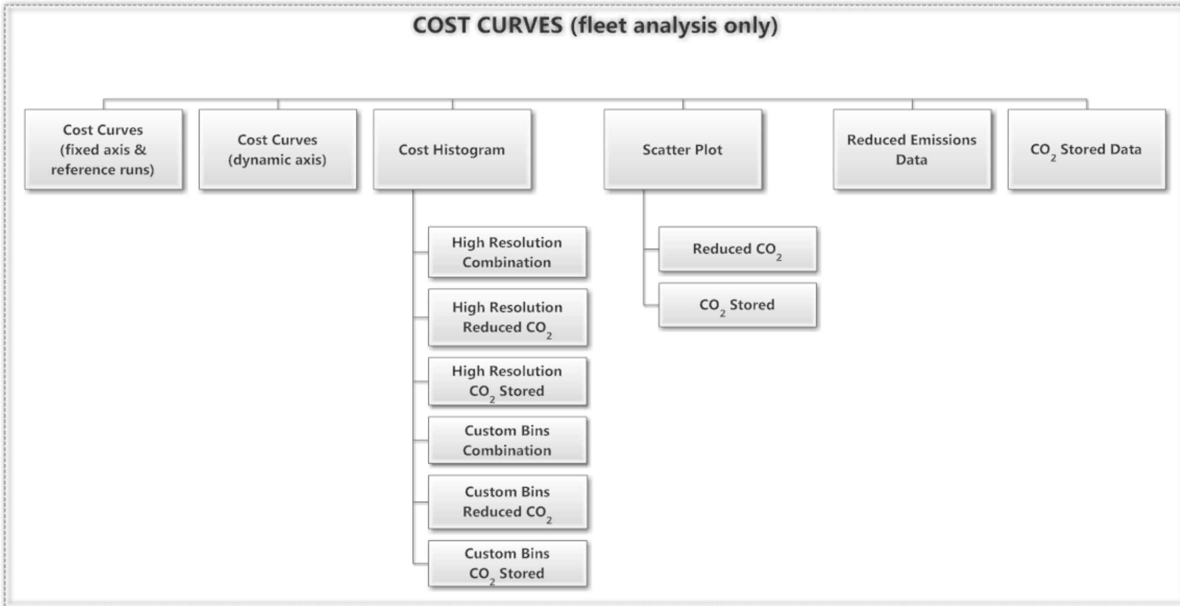

Figure 2b. WECSsim interface menu map, Cost Curves.[1]

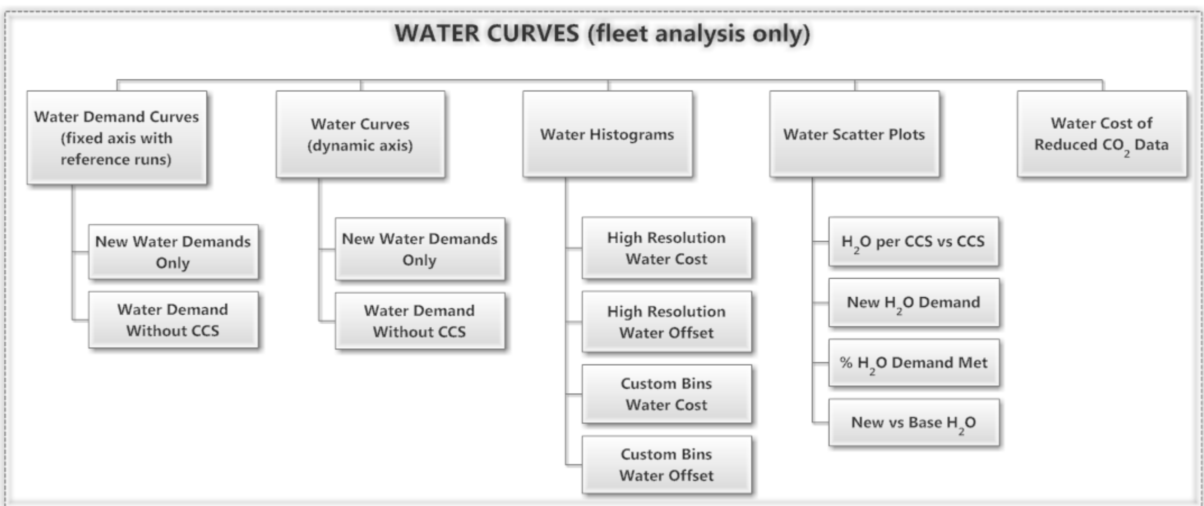

Figure 2c. WECSsim interface menu map, Water Curves.

[1] WECSsim distinguishes between the amount of CO_2 stored, and the amount of CO_2 reduced (avoided).

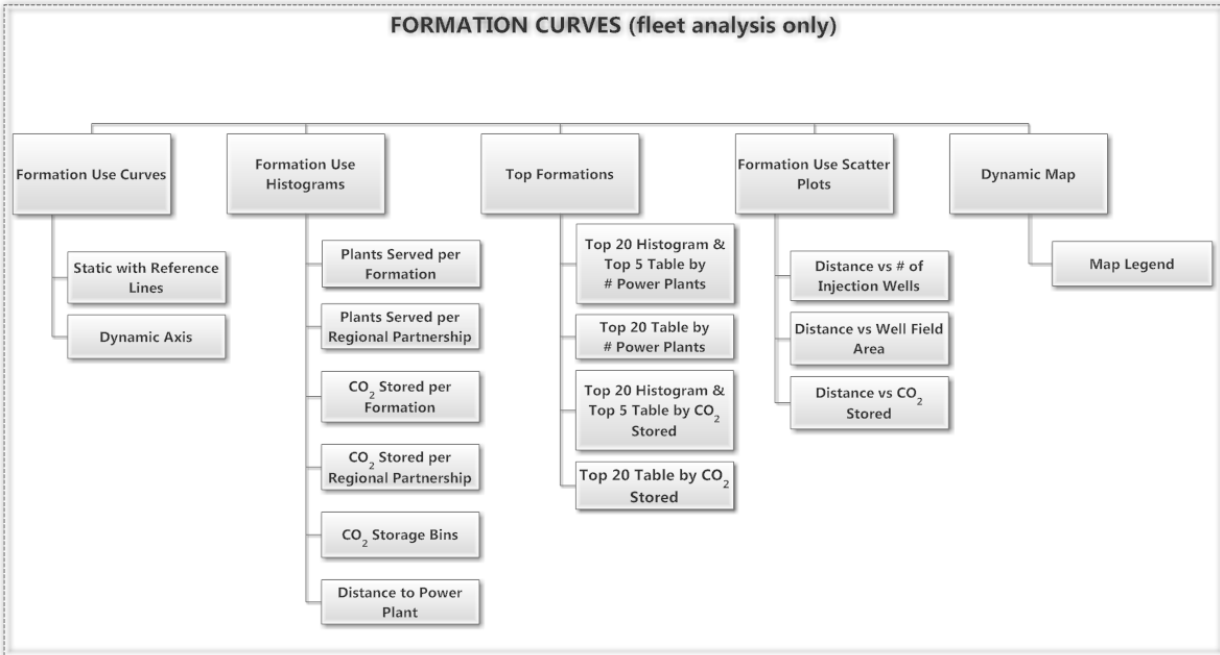

Figure 2d. WECSsim interface menu map, Formation Use.

Throughout WECSsim, the top interface level represents the module tabs. These include the Summary tab and the five module-specific tabs oriented horizontally across the top of the interface. Note that WECSsim has five modules, and the WECSsim interface has six upper level tabs. Module and tab are used throughout this document to refer to a distinct conceptual portion of the model, and a distinct portion of the user interface respectively.

The second interface level is a vertically oriented list in the upper left of the interface. In the case of fleet analysis, there is a third level of navigation shown in Figures 2b–2d and discussed in Section 8. Figure 2 shows the available interface screens, Figure 3 shows the home screen with the top interface tabs across the top, and Figure 4 shows an example screen with the tabs across the top as well as the second level navigation options in the upper left. Bold text shows the location of the user in the interface. Throughout the WECSsim interface, the convention holds that the upper part of the page represents model inputs that change with tab to tab and second level navigation changes, while the lower part of the page represents model outputs which only change from tab to tab. Third level navigation options are associated with extra output, and each page is unique.

1.5 WECSsim Introductory page

WECSsim opens with a home page listing the model's authors and other salient background information (Figure 3). A key option for the model user is to select the level of detail they are interested in with respect to the number and types of power plants to analyze. The first option allows users to explore any single, specific power plant by name (coal- or natural gas-based) in the U.S. for the performance and cost characteristics of a CCS system for any of the saline formations within the national database underpinning the model. The next two options allow the user to select only coal plants, or all coal and gas plants, but at a national level such that all plants will be simultaneously evaluated, ranked, and sorted based on their CO_2 and water requirement profiles for a given CCS scenario. In all cases, all saline formations in the database are potential storage targets for the power plant(s) under consideration.

Figure 3. WECSsim home page.

WECSsim's Single Power Plant Analysis Mode:
The simplest mode is the single power plant analysis mode in which the model user can specify an individual power plant, attributes of that plant, how much CO_2 capture is desired, attributes of the make-up power system, and aspects of brine extraction and treatment. From this information, WECSsim selects the CO_2 sink available with the lowest cost. The costs calculated include those for CO_2 storage, CO_2 avoided, and added water demands due to CCS that can be

offset by using the extracted, treated brine from the targeted formation. Sections 2–7 of this document develop from the perspective of a single plant analysis.

WECSsim's Fleet Analysis Mode:
The other mode of WECSsim is the fleet analysis mode. In fleet analysis mode, which is an extension of the single power plant analysis mode, WECSsim matches each power plant from the U.S. coal- and gas-fired fleet to a storage formation and calculates all associated costs and added water demands. Fleet analysis mode can be thought of as the single power plant analysis mode run over and over for each plant in the fleet. Running WECSsim in the fleet analysis mode only takes a few minutes depending on computer speed for the full fleet of 1126 power plants represented in the eGRID 2007 database (EPA, 2007). The fleet analysis is national in scale, but it can also focus on specific variables based on the model user's inputs. Note that any change to the model's default parameter settings applies to all power plants within the fleet. For example, imagine a power plant in Arizona for which the user would like to specify that make-up power be generated by Integrated Gasification Combined Cycle (IGCC) with tower cooling. This is easily done and evaluated in single power plant analysis mode, but if those changes are made in fleet analysis mode, make-up power for every plant in the fleet will be generated with IGCC and cooled with towers. If the model user decides to change the rated capacity of a power plant in fleet analysis mode, WECSsim will assign the user specified capacity to every plant in the fleet instead of using fleet data to populate the default capacities. It is important that the model user be aware of the fact that changing the model's defaults in fleet analysis mode has broad implications for calculations throughout the model when looking to adjust these default parameter assumptions. Section 8 of this document focuses on interface options specific to fleet level analysis.

2. SUMMARY SCREEN OPTIONS

Figure 4 shows the Overview page on the WECSsim Summary tab. The Summary pages provide a high level summary of key model inputs and outputs. The Overview page inputs include the option to choose any power plant from the 2005 U.S. Fleet (EPA, 2007) as a function of plant technology and the percent of CO_2 capture. WECSsim selects and displays the most economical formation for the selected power plant, how much CO_2 is stored, and the costs of storage and avoided emissions. The graphical output includes a map showing the power plant location and centroid location of the chosen saline formation, the fate of CO_2 before and after CCS, and the levelized costs of electricity (LCOE) before and after CCS. The double bar graph in the middle bottom showing CO_2 generation and emissions before and after CCS helps illustrate why the cost of CO_2 storage per mass stored is different from the cost of CO_2 emissions avoided per mass avoided. The dollars spent are equivalent, but CO_2 generation increases due to fossil fuel-based make-up power, which results in the mass rate of CO_2 storage being different than the change in CO_2 emission rates.

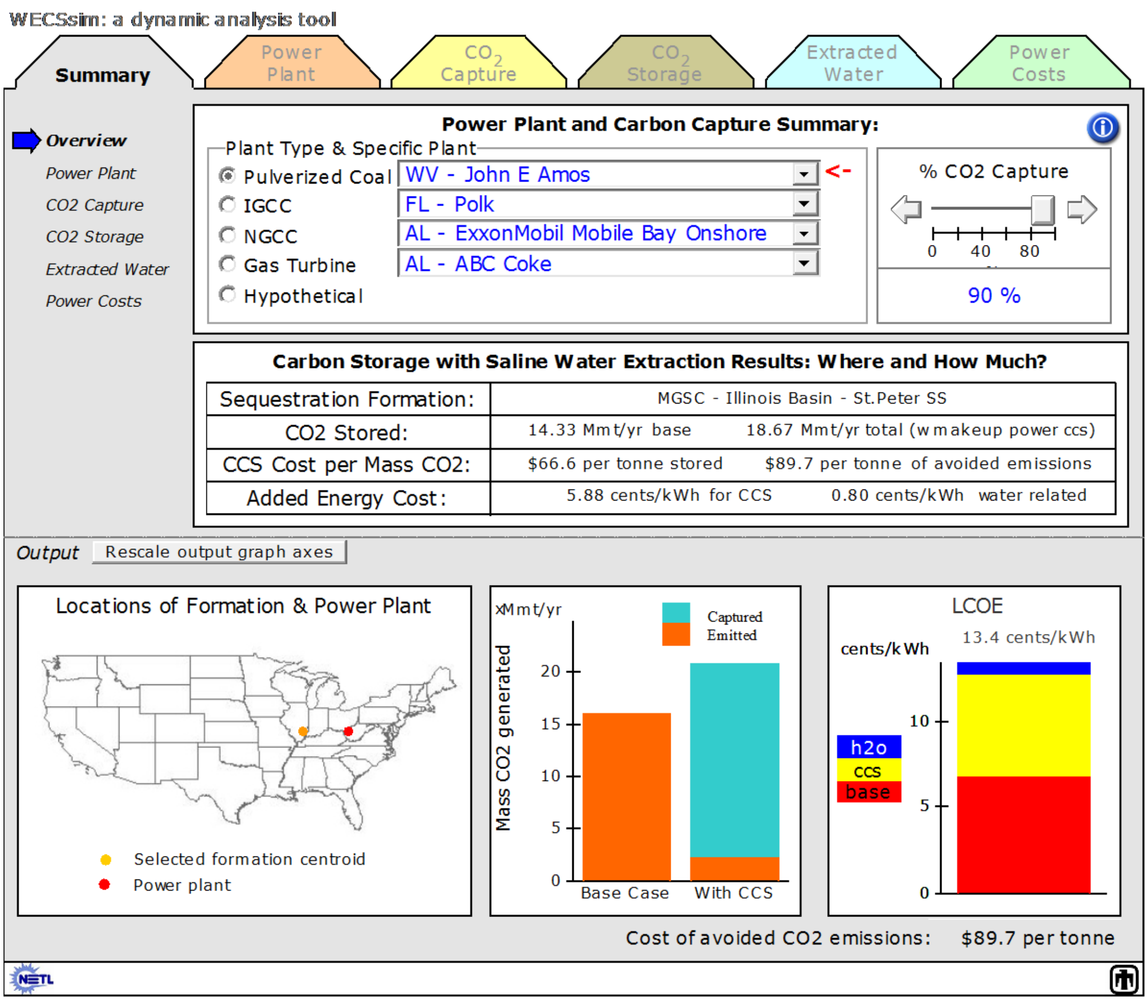

Figure 4. WECSsim Summary Tab, Overview Page.

Figure 4 shows a scenario of model defaults.[2] The LCOE ranges from 6.5 cents per kilowatt hour (¢/kWh) without CCS to 13.4 ¢/kWh with CCS and brine extraction and treatment. Avoided emissions costs are $89.7 per tonne CO_2. Input options available from the remaining pages on the Summary tab are the same as the Summary pages for each module tab, so to avoid repetition, the reader is referred to the Summary page descriptions in the next several sections.

[2] For more on model defaults and how to restore them, see Appendix G.

3. POWER PLANT OPTIONS

The Power Plant module in WECSsim is responsible for determining the location, electricity generation, CO_2 generation, water use, and base electricity costs for a given power plant. From the Power Plant tab, the WECSsim user can adjust any of these parameters. Defaults are typically based on values from an existing plant from eGRID 2007 (EPA, 2007).

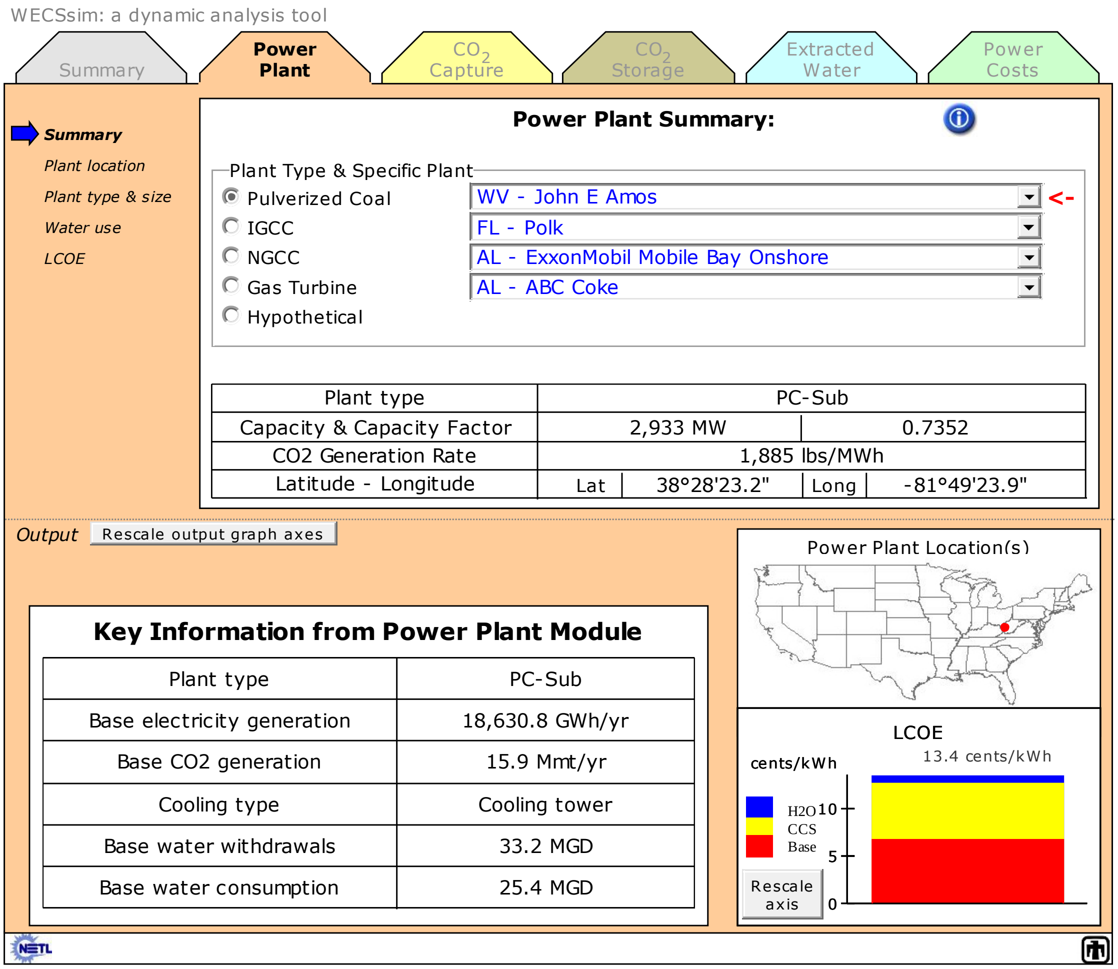

Figure 5. WECSsim Power Plant Tab, Summary Page.

Figure 5 shows the Summary page for the Power Plant tab from which the user can change the selected default plant and see the plant location, CO_2 generation rate, capacity, and capacity factor. Model outputs include a map showing the power plant location, a LCOE bar graph, and tabular output including base electricity generation, base CO_2 generation, cooling type, and water demand. The selected plant determines model defaults; however, the defaults can be changed from the appropriate second level pages. For example, Figure 6 shows a scenario testing increased efficiency per mass CO_2 produced (1,885 to 1,500 pounds per megawatt-hour (lbs/MWh)). Note that to change this value, the user must toggle the radio switches to "Custom", *and* change the blue custom number to the desired value. By convention, blue numbers in the interface can be manually adjusted by the user using the mouse and keyboard.

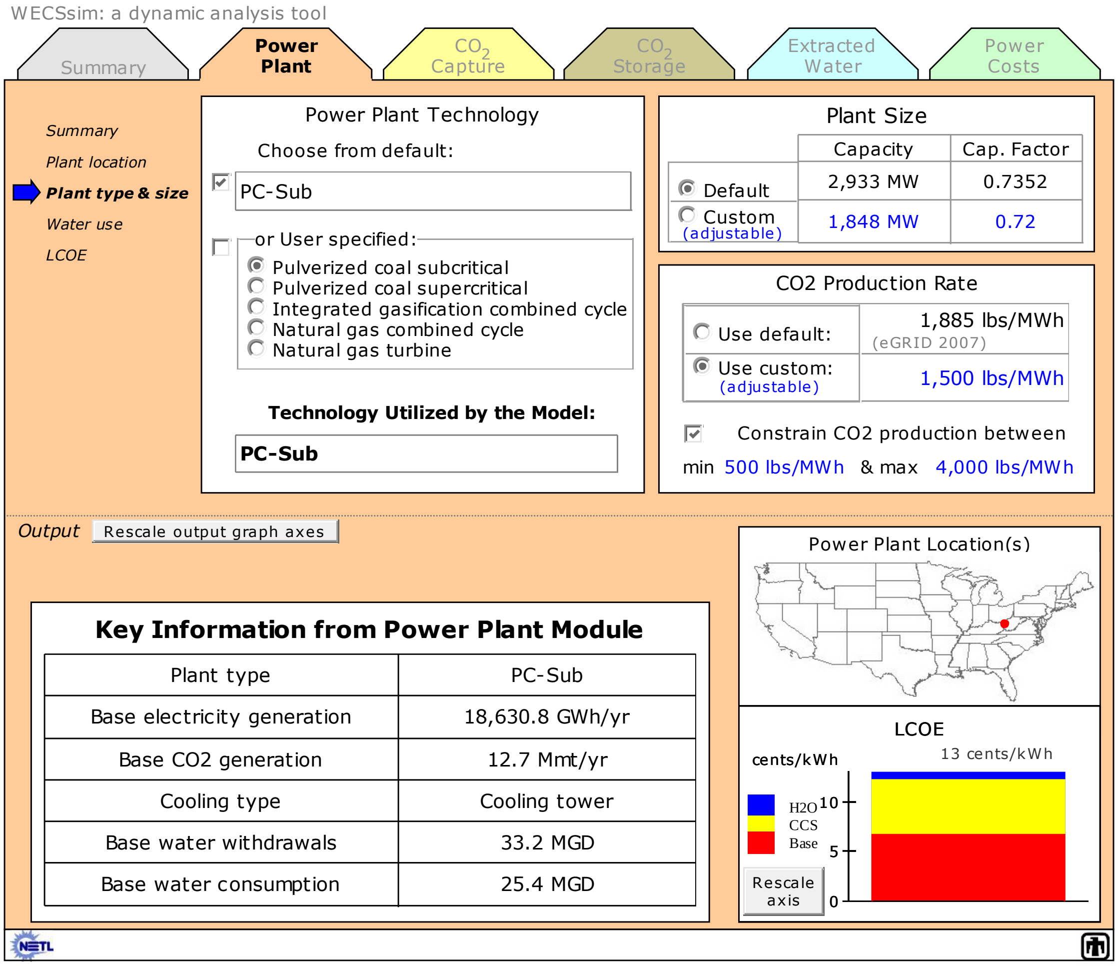

Figure 6. WECSsim Power Plant Tab – Plant Type & Size Page.

The improved efficiency scenario shown in Figure 6 results in a reduced LCOE for the plant with CCS (13 compared to 13.4 ¢/kWh) because of reduction in total CO_2 captured, transported, and stored, and therefore less brine extracted and treated as well. However, the cost of CCS per stored CO_2 or avoided CO_2 emissions rises to \$73.9 / tonne stored and \$106.5 / tonne of avoided emissions (from \$66.6/tonne and \$89.7/tonne, respectively, as seen in Figure 4). This is because there is less CO_2 captured at a 90% capture rate (11.41 compared to 14.33 million tonnes per year (Mmt/yr) not including make-up power), and thus fewer potential economies of scale associated with CO_2 capture and transport. Thus, energy per CO_2 efficiency reduces costs of CCS from the perspective of LCOE but increases them in terms of cost per mass rate of CO_2 storage or emission reductions. The subtlety of these changes as a result of a single input change underscores the importance of changing only one input at a time.

Inputs and assumptions associated with plant location, water demands, and base LCOE assumptions can be changed from the other pages in the Power Plant tab.

4. CO_2 CAPTURE OPTIONS

The CO_2 Capture module receives information on electricity and CO_2 generation for the power plant from the Power Plant module (See Figure 3). In the CO_2 Capture tab of the WECSsim interface, the model user decides what percent of the generated CO_2 to capture, the parasitic energy requirements associated with that capture, and what make-up power options will be used to offset these energy requirements in order to maintain net electricity generation.

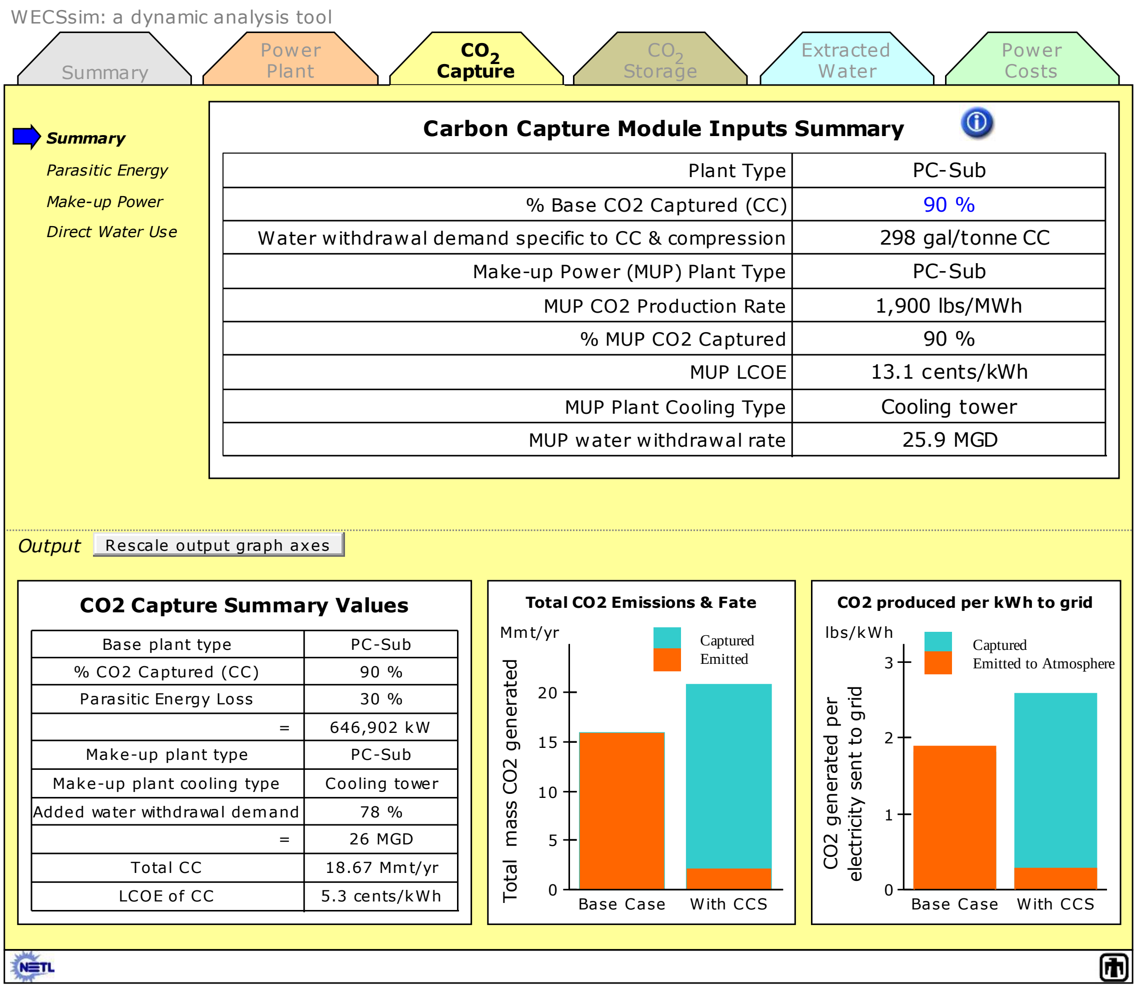

Figure 7. WECSsim CO2 Capture – Summary Page.

Figure 7 shows the Summary page of the CO_2 Capture tab. The default CO_2 generation at the power plant of 1,885 lbs/MWh from eGRID (EPA, 2007) has been restored, so once again the user evaluates the base case scenario. The CO_2 Capture tab shows that by default, 90% of emissions will be captured at both the original (John E. Amos power plant in West Virginia) and make-up power (MUP) plants. By default, WECSsim chooses the same plant and cooling technology for the MUP plant as for the target plant, and thus in this case, MUP will be supplied from a subcritical pulverized coal plant cooled with cooling towers. Determining the parasitic energy demand and how that demand will be generated are the two most important results of the

CO_2 Capture module. The Parasitic Energy page within the CO_2 Capture tab is shown in Figure 8.

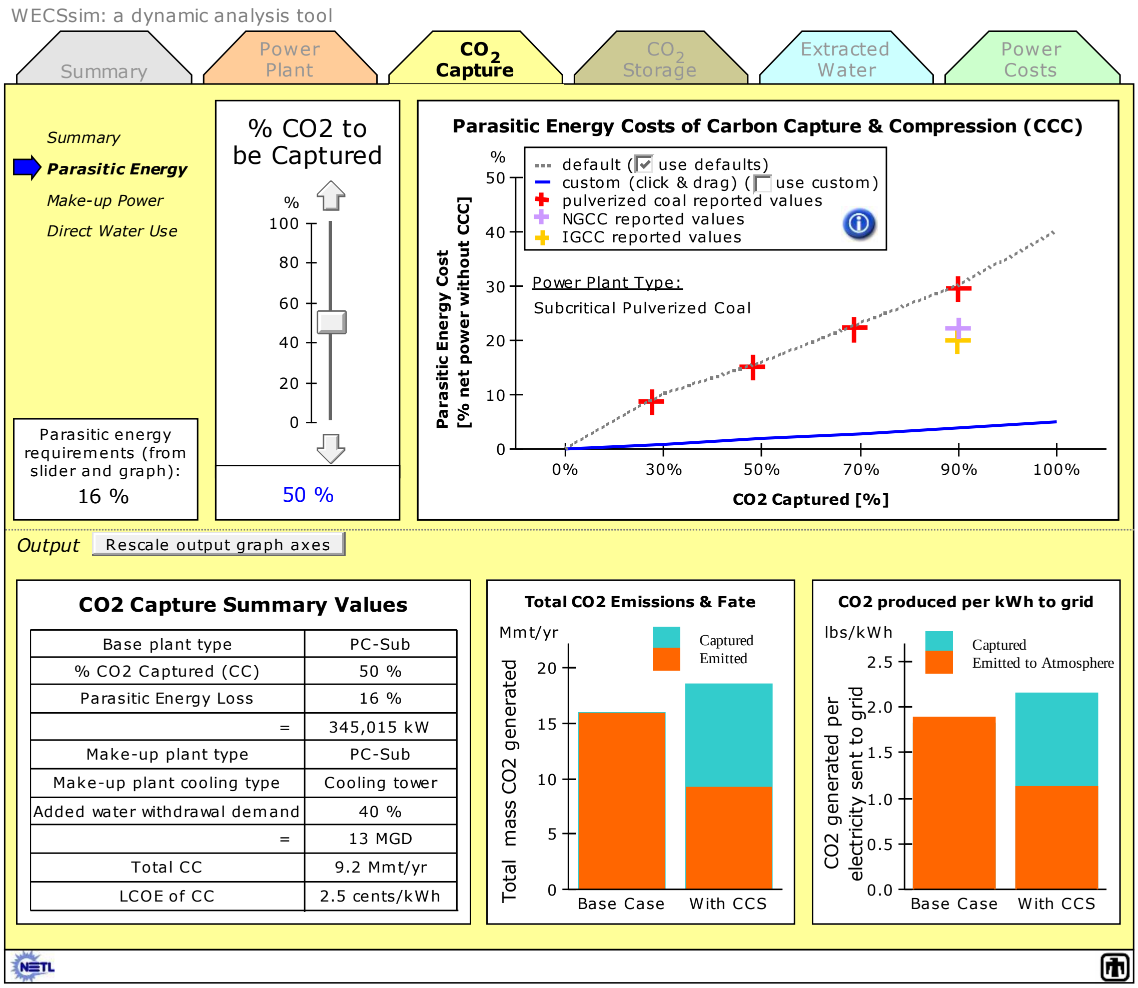

Figure 8. WECSsim CO_2 Capture – Parasitic Energy Page.

In this case, the default of 90% CO_2 capture has been changed to 50% at both the original and MUP plants. This value can be changed with the slider bar or by changing the blue numbers below the slider bar. Comparing Figure 7 and Figure 8 illustrates that when this change is made, the parasitic energy requirements drop from 30% to 16% of net power plant generation, and total CO_2 capture drops from 18.67 to 9.2 Mmt/yr.

WECSsim uses the user specified percent of CO_2 to be captured to find the parasitic energy loss as a fraction of net power using the relationship shown in the upper right of Figure 8. WECSsim will use either the default relationship (dashed black line) or a custom relationship (solid blue line) that can be moved by the user by clicking on it and dragging the 0%, 30%, 50%, 70%, 90%, and 100% points. The WECSsim default line changes based on plant type, and the colored crosses on the graph represent data points from various NETL studies for reference. Make-up power required to offset parasitic energy losses results in the bulk of added costs and water demands associated with implementation of CCS. Thus, WECSsim bottom line costs are driven to a large degree by the calculation of parasitic losses on the Parasitic Energy page of the CO_2

Capture tab (Figure 8), and the calculation of resulting MUP costs and water demands defined on the Make-up Power page of the CO_2 Capture tab shown in Figure 9.

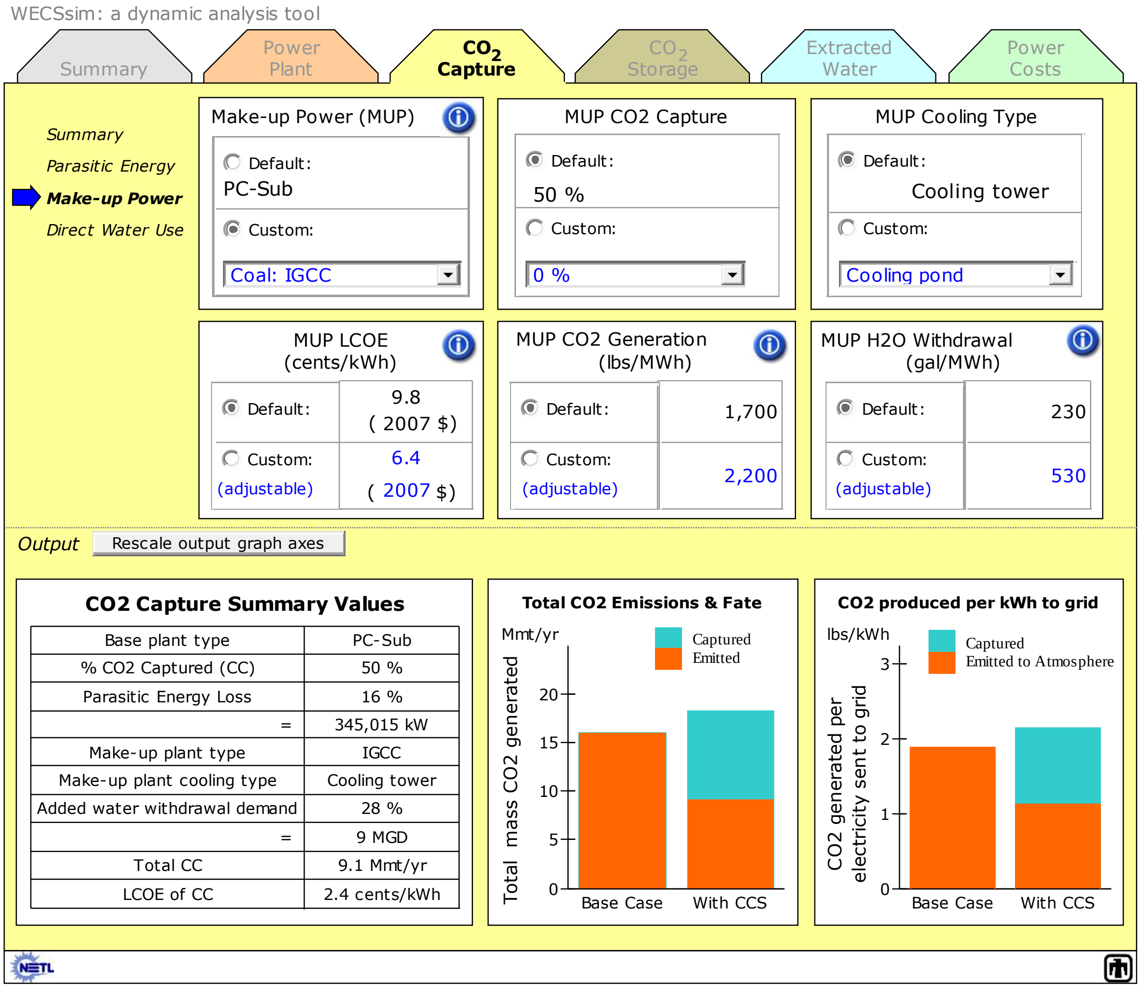

Figure 9. WECSsim CO_2 Capture – Make-up Power Page.

On the CO_2 Capture – Make-up Power tab (Figure 9), the model user can select the MUP plant type, how much CO_2 to capture at the MUP plant, how the MUP plant is to be cooled, the LCOE of the new power, and the CO_2 generation rate and water withdrawal demand of the MUP plant. Figure 9 shows a scenario in which the MUP plant type has been changed from the default pulverized coal to IGCC. Note that as compared to the scenario shown in Figure 8, the LCOE costs associated with CO_2 capture have dropped slightly (from 2.5 to 2.4 ¢/kWh) because IGCC MUP costs are less than pulverized coal if 50% or more of the CO_2 from the MUP plant is to be captured. The model user can see this effect in the default MUP LCOE values on the Make-up Power page of the CO_2 Capture tab by adjusting the MUP CO_2 capture amount and toggling between pulverized coal and IGCC MUP plant types.

Added water demands associated directly with CO_2 capture (not resulting from MUP generation) can be adjusted on the Direct Water Use page of the CO_2 Capture tab.

5. CO_2 STORAGE OPTIONS

The CO_2 Storage module receives information on total CO_2 capture and location of that capture (e.g., which power plant) from the CO_2 Capture and Power Plant modules (See Figure 1). With this information, the CO_2 Storage module calculates the transportation distances for the CO_2 to any of the 325 NatCarb 2008-based saline formations (see Appendix C) or a hypothetical saline formation as specified by the model user. The total pore space resource of each saline formation (also referred to here as sink) is calculated based on the volume of pores (area × thickness × porosity). With geologic properties of the sink, the model user specification of open or closed formation boundaries, and whether or not brine is being extracted simultaneously with CO_2 injection, WECSsim calculates the average volumetric storage efficiency (the portion of pore space in the formation that can be filled by CO_2) expected for each formation. Pressure and temperature in the CO_2 sink (based on depth) are used to calculate steady state density of the injected CO_2 in the formation. The volumetric pore resource for CO_2 storage in each potential sink is multiplied by the density of injected CO_2 in that sink to get an estimate of the mass of CO_2 that could be stored in each formation, either as a total or per unit area of formation. WECSsim then combines this mass storage potential with the rate of CO_2 capture to get the rate at which the power plant in question would fill any of the possible saline formations. Finally, the formation permeability and thickness are used along with a specified injection well field lifetime to find the well spacing in the well field and injection rate for each well. This calculation is iterative because well spacing affects injection rate, and injection rate determines total well numbers required, which determines well spacing. See Appendix F for more details on injectivity related calculations. The permeability of the formation can be deterministic, or stochastic by individual well or entire well field. The relative complexity of these calculations explains why the CO_2 Storage tab is more complex, with eight 2nd-level pages as compared to four for the Power Plant tab and three for the CO_2 Capture tab. Indeed, development of the CO_2 Storage module represented a sizable undertaking within the overall development of WECSsim, which is reflected in the complexity of the CO_2 Storage interface tab.

The value of these calculations is that the CO_2 Storage module calculates the distance from the specified power plant to each available sink, the number of injection wells required at each available sink, the sink resource utilized per time, and the pipe sizes and lengths required to move CO_2 within the injection well field. All of this information, along with information on brine extraction and treatment from the Extracted Water module, are used in the Power Costs module to select the most economical saline formation to store CO_2 for a given power plant scenario. This is the WECSsim selected formation that is listed as the CO_2 Storage Target in the CO_2 Storage tab Summary page as shown in Figure 10, and the default CO_2 Storage Target in the CO_2 Storage tab Sink ID and Location page shown in Figure 11. Figure 10 shows that for the John E. Amos power plant base case scenario, the St. Peter Sandstone formation, located approximately 230 miles away from the power plant, is selected as the most economical formation. Note that the geometric mean permeability of the formation is estimated at 316 mD, and only 10 wells are required to inject the 18.7 Mmt/yr CO_2 to be stored.

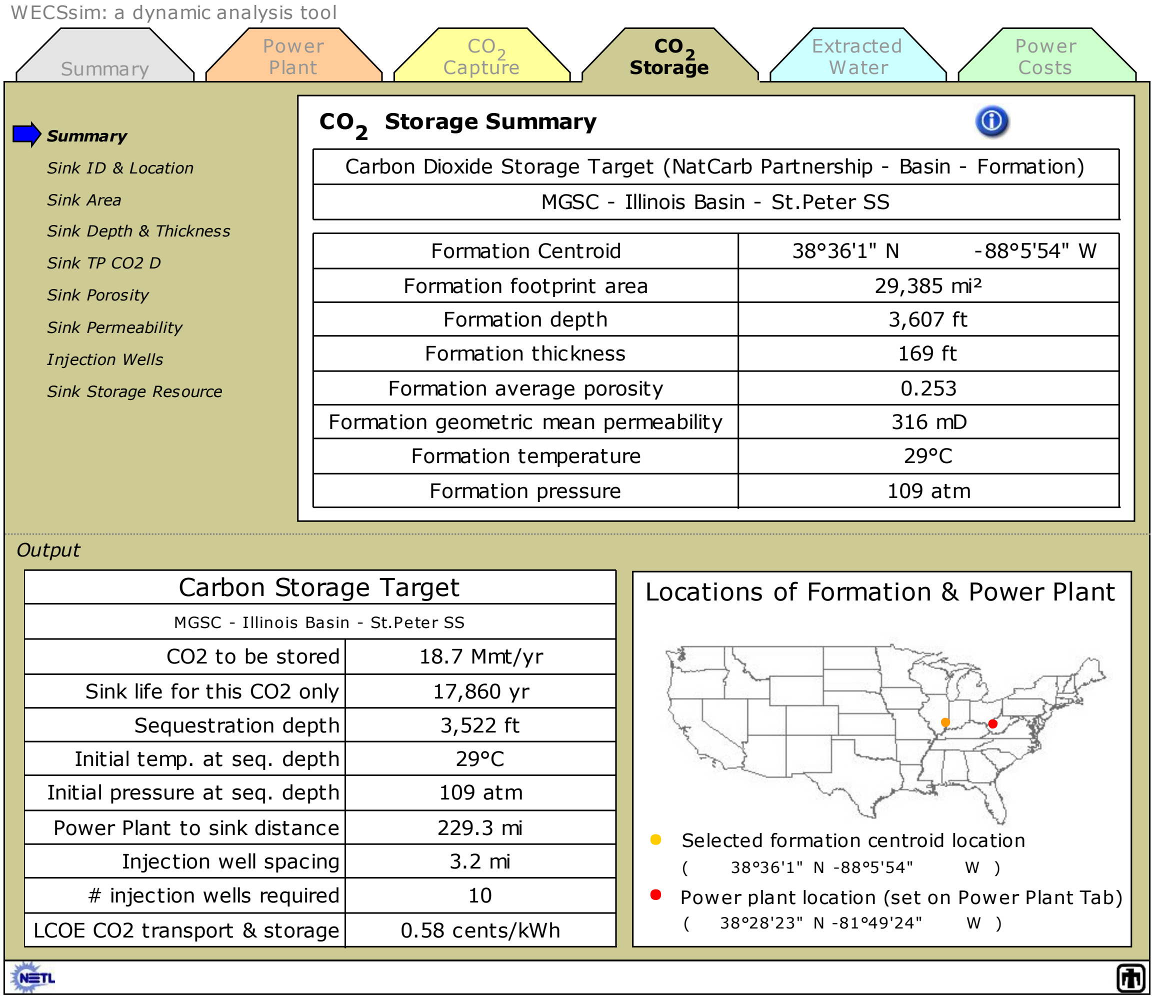

Figure 10. WECSsim CO_2 Storage – Summary Page.

The Plant location page on the Power Plant tab gives a list of the closest five saline formations to the power plant, and in this case, the St. Peter Sandstone is fourth on that list. Why didn't the model choose a closer formation? The answer lies in the tradeoff between the costs of moving CO_2, the costs of injecting CO_2 and extracting brine, and the quality (or lack thereof) of the brine. Figure 11 shows input options for the sink location, including an option to limit the distance that CO_2 (and brine) will be moved between the power plant and saline formation and vice versa to (an adjustable) 50 miles. Selection of that option forces the model to use a closer formation with a much lower mean permeability (5 mD used in Figure 11 (not shown) compared to 316 mD shown in Figure 10), and as a result, 982 injection wells are required such that despite the power plant overlying the saline formation, the CO_2 transport and storage costs increase from 0.58 to 2.41 ¢/kWh. This example shows that an arbitrary limit on the distance between power plant and formation may have very detrimental implications on costs associated with CCS at power plants that are not close to high quality CO_2 sinks.

Default sink shape (in two dimensions) and resulting footprint area is displayed and can be adjusted in the Sink Area page of the CO_2 Storage tab. Boundary conditions for the formation, either open or closed are also specified in the Sink Area page of the CO_2 Storage tab. The Sink

Depth & Thickness page of the CO_2 Storage tab is shown in Figure 12. Model defaults for the John E Amos power plant have been restored. Only two parameters are shown here: depth and thickness; however, because of a paucity of data for these parameters, there are four potential sources for these numbers. The preferred default, and one that exists for the St. Peter Sandstone, is a value reported by one of the Regional Carbon Sequestration Partnerships. If a reported value exists, it is used as the default. If it is not reported, a value from a subset of potentially intersecting wells (labeled “SNL wells”) becomes the default if available. The SNL wells in this case are only available for a handful of formations either deemed to be important potential storage targets or formations for which no depth or thickness information was reported. If no information for depth or thickness was reported or developed with a subset of potentially intersecting wells, then results from all potentially intersecting wells are used. See Appendix D for more information on the process used to develop these parameters from well records, either by using all potentially intersecting wells, or a subset thereof. If there are no potentially intersecting wells and no reported information, then no information is available to WECSsim, and the formation will not be selected unless the user specifies a depth and or thickness in the custom option. Be aware, however, that if the custom option is selected for depth or thickness, it sets the depth or thickness of all saline formations to the custom value.

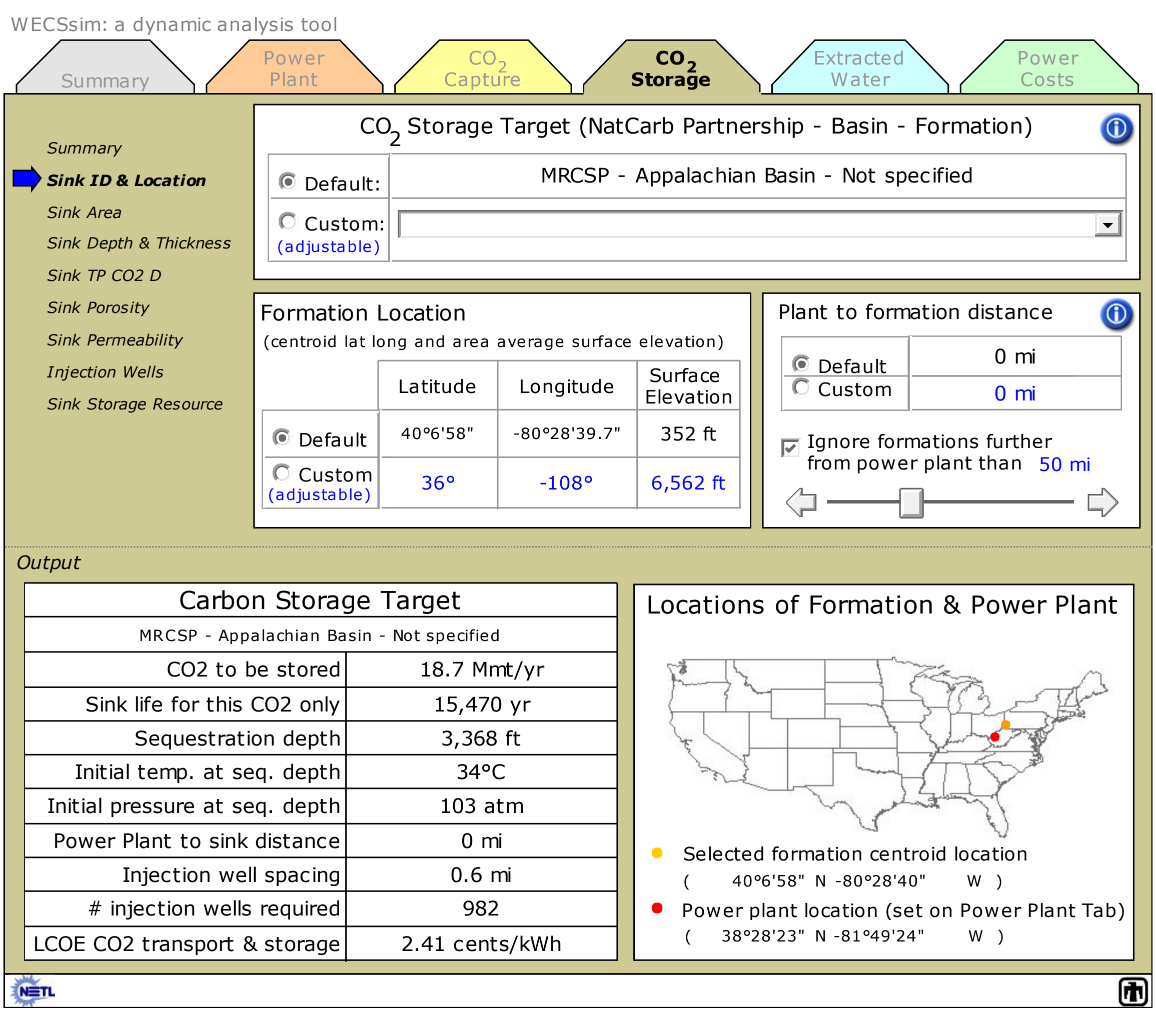

Figure 11. WECSsim CO2 Storage – Sink ID & Location Page.

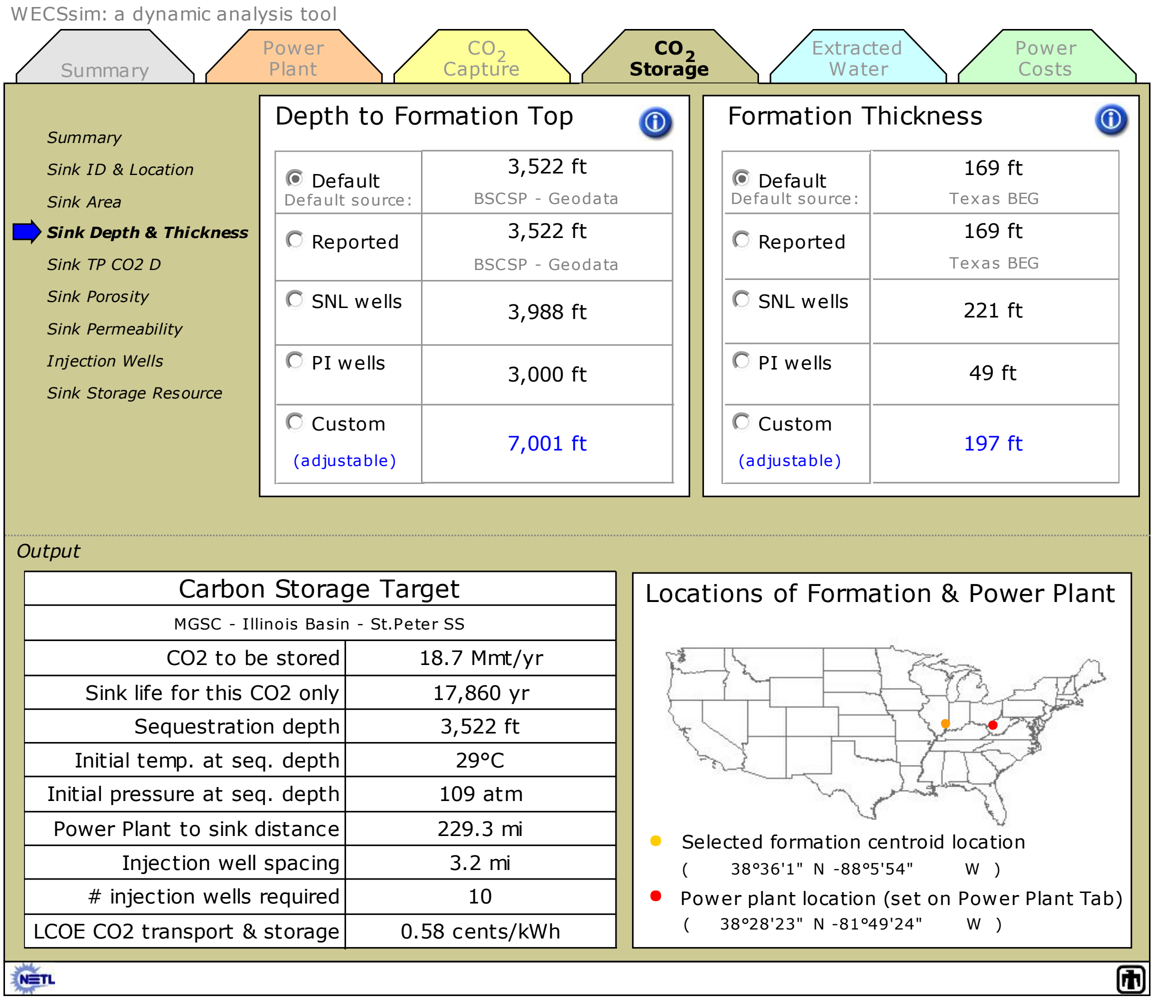

Figure 12. WECSsim CO_2 Storage – Sink Depth & Thickness Page.

Default background, injection, and fracture pressures for the saline formation, along with formation temperature and resulting CO_2 density expected in the formation, are parameters displayed and adjustable in the Sink TP CO2 D page of the CO_2 Storage tab. Default porosity values are displayed and changeable in the Sink Porosity page on the CO_2 Storage tab shown in Figure 13.

Figure 13 introduces the notion of rock type composition of the saline formations. Porosity and permeability data were very limited for the 325 NatCarb 2008-based polygons developed for WECSsim's CO_2 Storage Module. To actively address this data limitation, each polygon was classified as made up of some fraction of four different rock types: clean sandstone, dirty sandstone, carbonate, and Gulf Coast. Additionally, a typical range of porosity and permeability were associated with each rock type. For an in-depth discussion on the classification of polygons by rock type and the association of porosity and permeability distributions to a given rock type, see Appendix E.

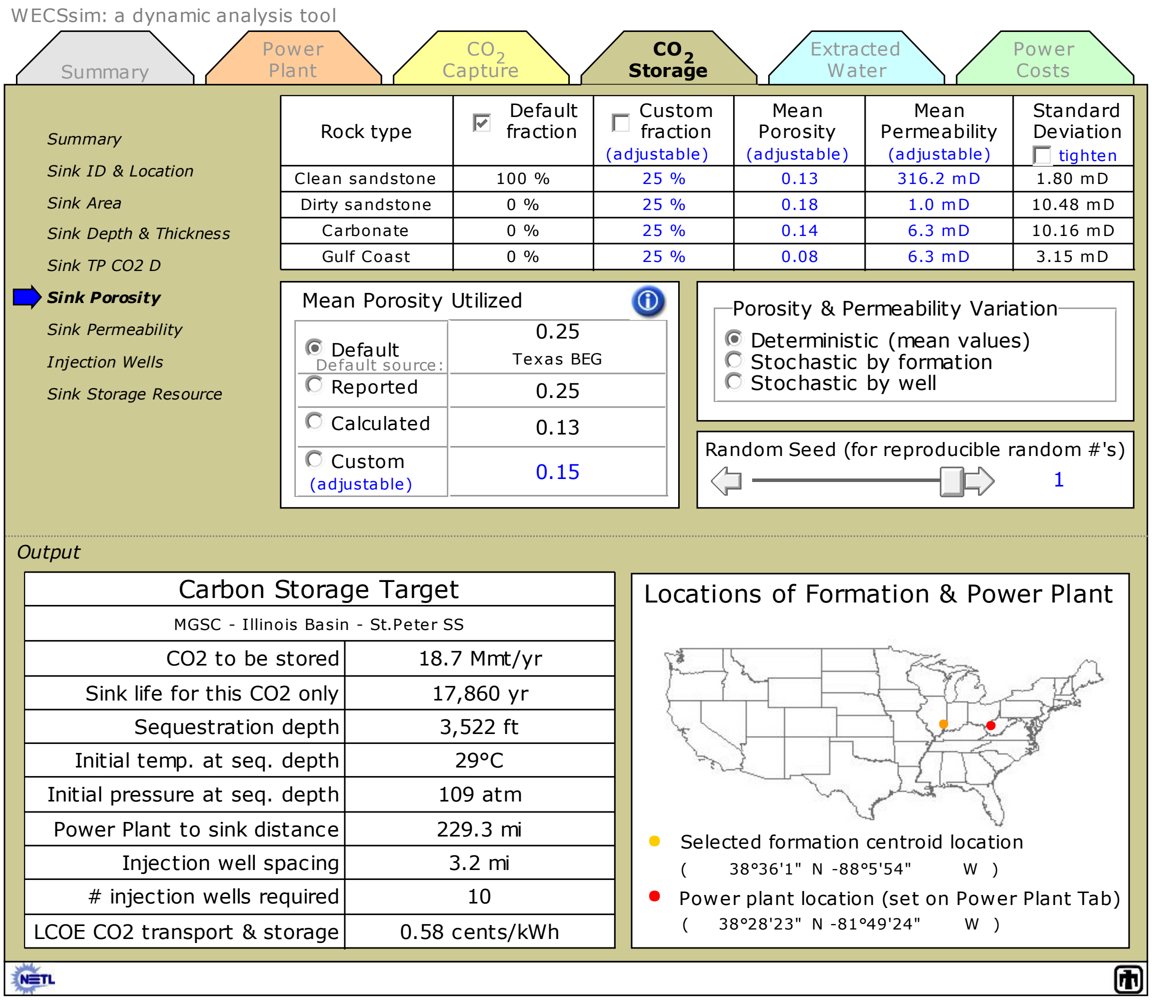

Figure 13. WECSsim CO_2 Storage – Sink Porosity Page.

Figure 13 shows that by default the St. Peter Sandstone is classified as 100% clean sandstone, and thus WECSsim calculates a mean porosity of 0.13. In this case, a reported value of 0.25 is available, and so it is used as the model default instead of the calculated 0.13. The model user can override this choice by clicking on the alternate estimates for porosity or entering a custom value. The user can also change the assumed rock mix associated with a given saline formation. As an example, Figure 14 shows the results of changing the default rock type mix to 50% clean and 50% dirty. The result is initially unexpected: WECSsim changed the target formation to the Appalachian Basin. The reason for this is that when the user changes the default rock mix, the specified rock mix is applied to every formation in the model, and the St. Peter Sandstone now is assigned the same average porosity and more importantly, average permeability, as the closer Appalachian Basin formation. This scenario underscores the important point (also made earlier) that when model defaults are changed, the change cascades across all saline formations (or all power plants) and may change model results in more ways than expected.

If the intention of the user is to see what the change to costs would be if the Saint Peter Sandstone is not as close to clean sandstone as assumed, the user must force WECSsim to consider the Saint Peter Sandstone only. This can be done with the custom dropdown in the Sink

ID & Location page of the CO_2 Storage tab shown in Figure 11. Figure 15 shows the results of this change. Making the St. Peter Sandstone 50% dirty would increase the number of injection wells required from 10 (Figures 11–13) to 20, and the costs of CO_2 transport and storage from 0.58 to 0.61 ¢/kWh.

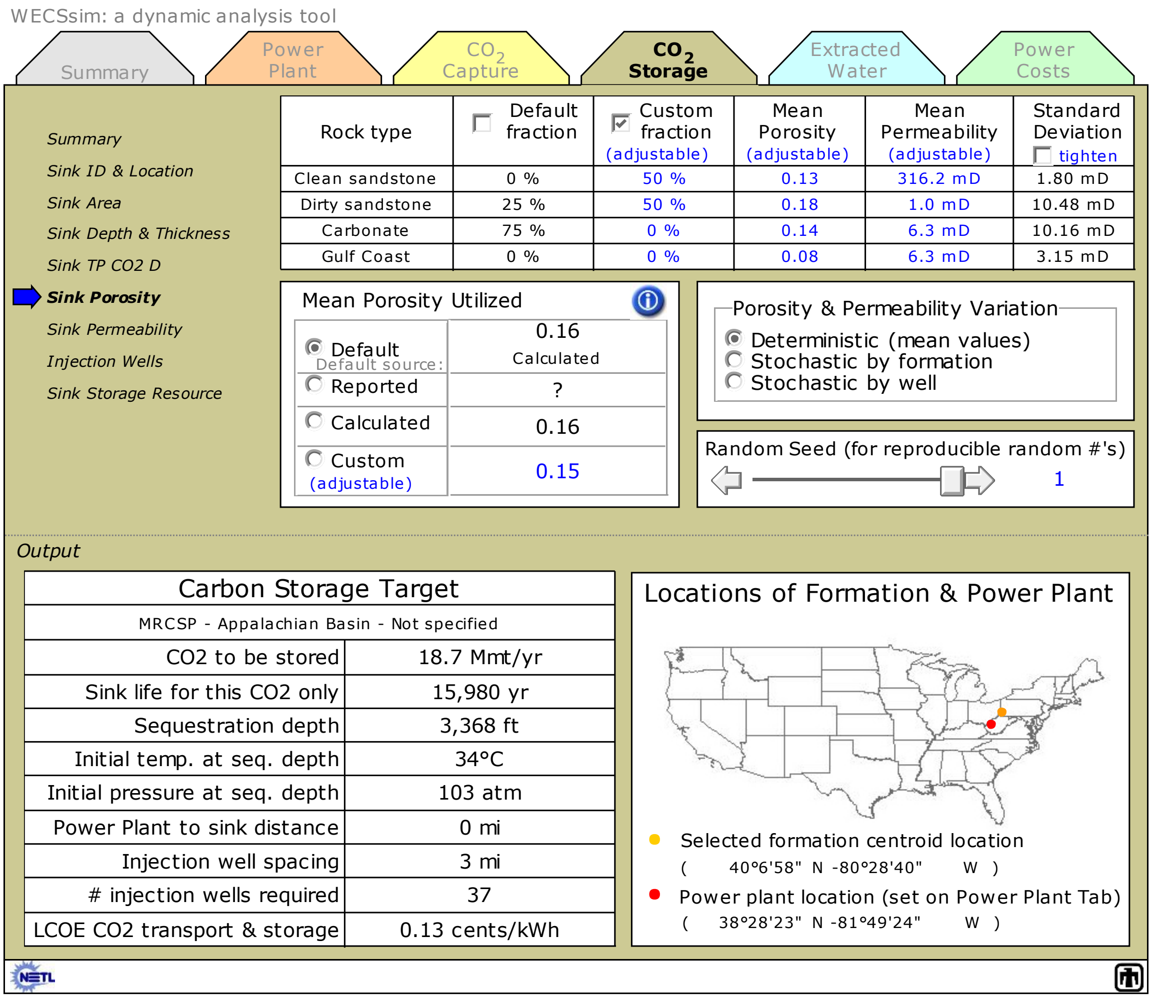

Figure 14. WECSsim CO_2 Storage – Sink Porosity Page, Custom Rock Type Fraction.
Note: A change to custom rock type mix then changes the target formation because the custom change is applied to all formations, and the geologic performance advantage of the St. Peter Sandstone supersedes the geographic advantages of closer formations.

In Figures 13–15, it is important to note that each rock type has an associated mean porosity and permeability as well as a standard deviation. The porosity values are assigned to a normal distribution with the given values, and the permeability values are assigned to a distribution that is normal in log space with the given values. It is also important to note that the default mean porosity values vary from 0.08 (for Gulf Coast rocks) to 0.18 (dirty sandstone) across rock types. This is a very small range relative to the default range for mean permeabilities across rock type (1 to 316 mD). Thus, changing the assumed rock type mix is likely to influence the number of wells required more so than the portion of a formation's pore space required. The distribution parameters associated with each rock type can be adjusted individually, or all distributions can be 'tightened' automatically by clicking on the box above the list of standard deviations. See

Appendix E for more information on how the default distributions were developed. In addition to choosing a log normal permeability distribution with a mean and standard deviation on the Sink Porosity page, a custom permeability distribution can be built by the model user on the Sink Permeability page of the CO_2 Storage tab.

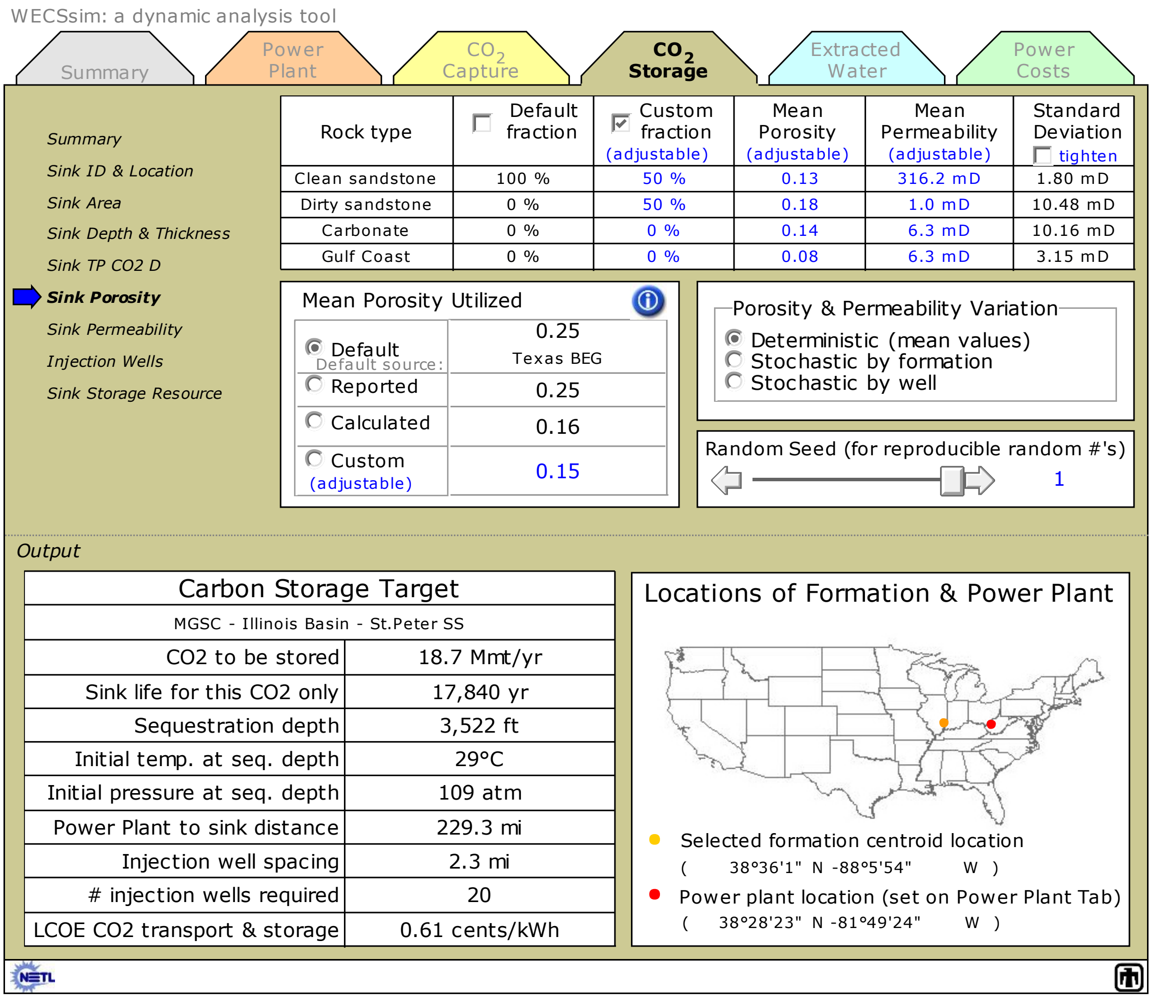

Figure 15. WECSsim CO_2 Storage – Sink Porosity Page, St. Peter Sandstone.
Note: A change to custom rock type mix but with the target formation forced to be the St. Peter Sandstone.

Using distributions for porosity and permeability allow WECSsim to sample randomly from the porosity and permeability distributions to get a range of model output as a result of geologic uncertainty. The model user can choose either to have no stochasticity at all with respect to porosity and permeability, or that all wells in a well field have the same randomly selected porosity and permeability values ("stochastic by formation"), or that the porosity and permeability of each well are sampled randomly from the distribution ("stochastic by well").

The Injection Wells page of the CO_2 Storage tab has information related to the number of injection wells calculated, the fraction of the injection well casing that is screened, whether or not brine is to be extracted, the lifetime of the injection wells, and the odds of drilling a useable bore hole based on water quality considerations. The choice to extract or not extract brine, and the water quality considerations associated with injection and extraction wells will be explained in the next section.

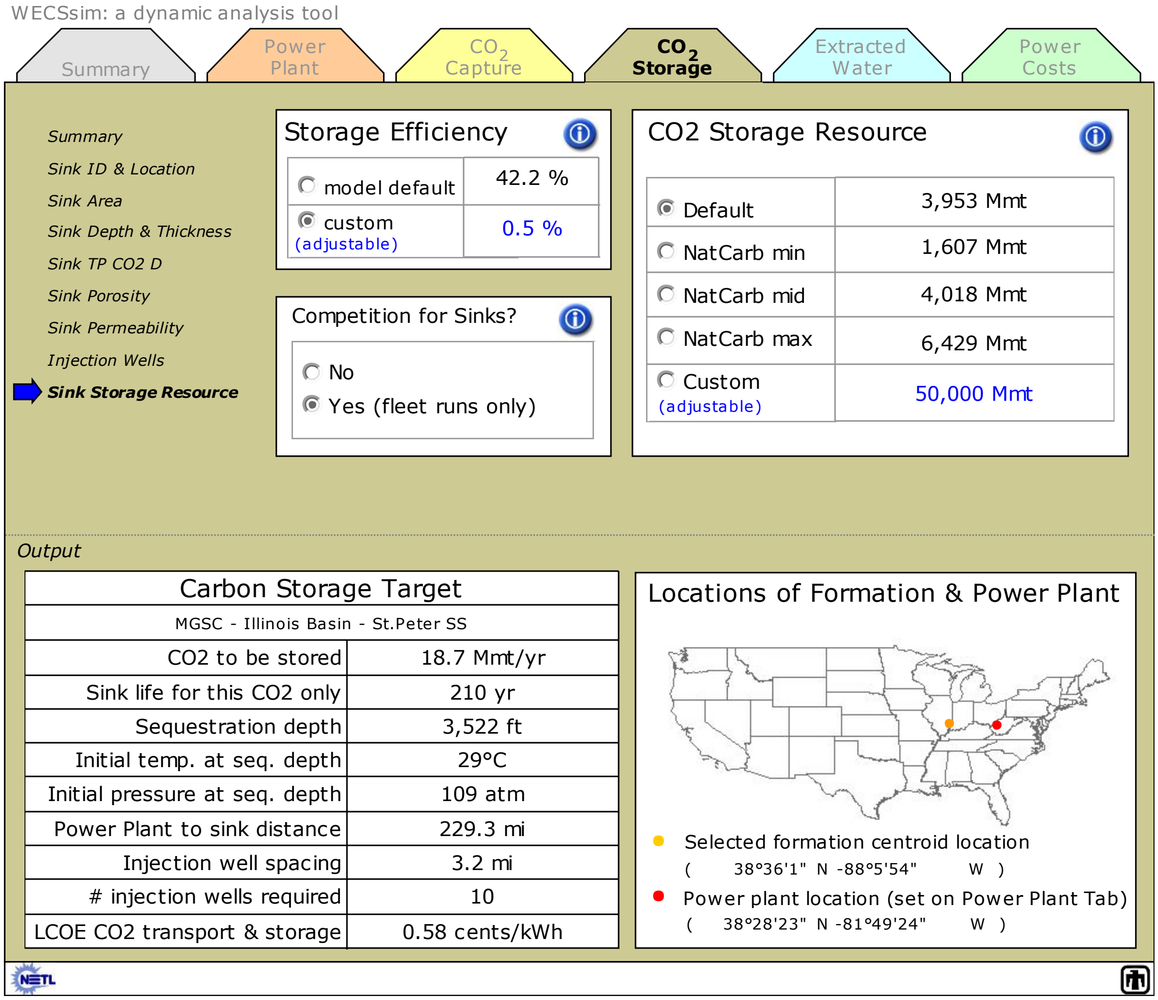

Figure 16. WECSsim CO_2 Storage – Sink Storage Resource Page.

Figure 16 shows the Sink Storage Resource page on the CO_2 Storage tab. The scenario shown in Figure 16 is back to the John E. Amos power plant base case, except now a custom storage efficiency of 0.5% is selected rather than the model default 42.2%. This changes the sink life for the John E. Amos plant from 17,840 years when the large formation is used efficiently, to only 210 years, and also brings the default CO_2 Storage Resource estimate for the St. Peter Sandstone down to approximately 4,000 Mmt total—very close to the NatCarb middle (mid) estimate as seen in the table in the upper right of Figure 16. Brine extraction plays a very large role in storage efficiencies. In the Extracted Water module, the WECSsim user can evaluate the impact of this brine extraction on the cost and performance of CCS.

6. EXTRACTED WATER OPTIONS

One of the fundamental goals of WECSsim is to help understand and quantify the costs and benefits that would be associated with simultaneous extraction of brine from the storage formation during CO_2 injection. Brine extraction does add to the overall systems' costs, but the benefits include more efficient storage of CO_2 in the storage formation, reduced pressure build up in the formation, and a new water source to help offset added water demands associated with the parasitic energy requirements to capture CO_2. By default, WECSsim extracts brine while injecting CO_2 to the target formations. Figure 17 shows the Summary page of the Extracted Water interface tab. The model defaults for John E Amos power plant have been restored.

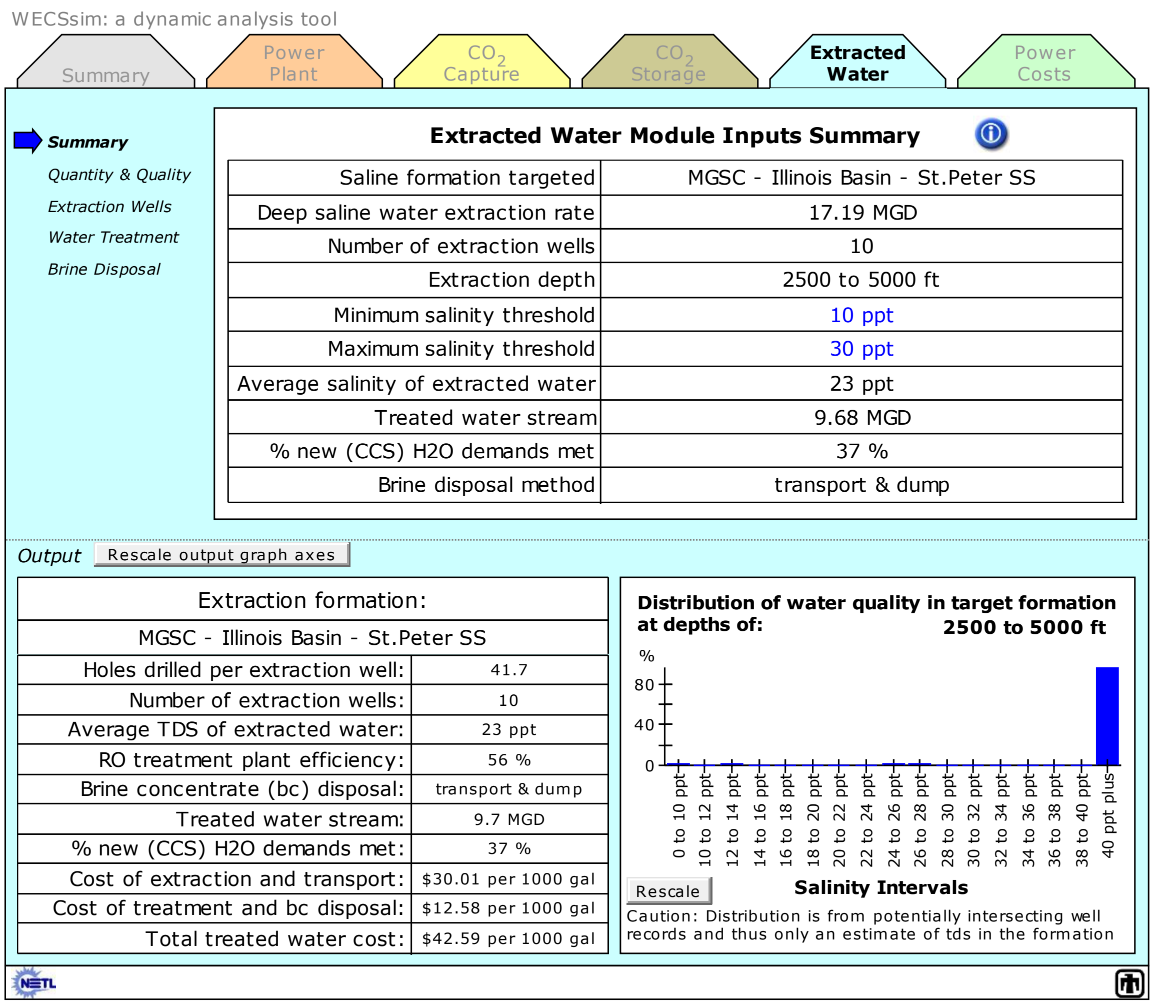

Figure 17. WECSsim Extracted Water - Summary Page.

Water quality considerations play a substantial role in the evaluation of brine extraction options. Specifically, EPA regulations to protect potential drinking water sources require that no CO_2 injection is to occur in saline formations where the total dissolved solids (TDS) levels are less than 10,000 parts per million (ppm) (same as 10 parts per thousand (ppt), or 1%) (EPA, 2010). On the other end of the spectrum, high salinity waters (40 ppt +) are relatively expensive to treat compared to, say, seawater. Note the histogram of water quality information for the Saint Peter

Sandstone shown in the lower right side of Figure 17. The poor water quality in this formation results in high drilling costs, high TDS (23 ppt) water being treated, a resultingly low efficiency of treatment (56%), and therefore a large amount of brine concentrate for disposal. Implications of this water quality distribution can be explored in the other pages of the Extracted Water tab discussed in the remainder of this section.

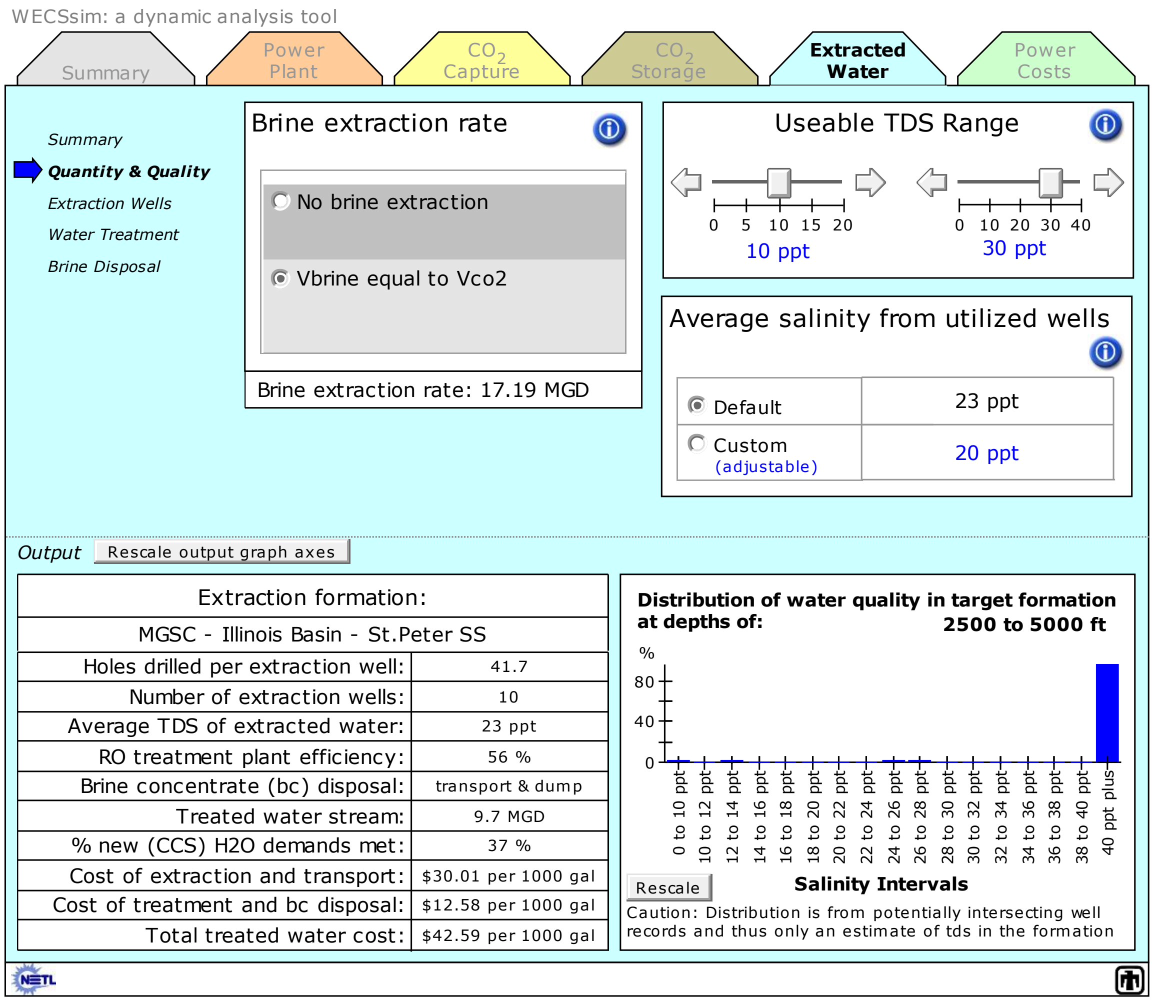

Figure 18. WECSsim Extracted Water – Quantity & Quality Page.

WECSsim provides a user specified range of brine salinities that are targeted for extraction. The default range of 10–30 ppt can be adjusted from the Quantity and Quality page on the Extracted Water tab shown in Figure 18. This page also allows the user to decide whether or not to extract brine at all. (This brine extraction switch is also available from the Injection Wells page on the CO_2 Storage tab.) For the single plant analysis, costs can usually be reduced by not extracting brine. However, when multiple plants are seeking CO_2 storage targets, the added efficiency of formation use associated with brine extraction can become compelling.

Because WECSsim will only use water between 10–30 ppt, but the formation is composed mostly of water with total dissolved solids greater than 40 ppt (as seen in the histogram on the bottom right side of Figures 17 and 18), the results indicate on average almost 42 holes must be drilled before water of an appropriate quality is found as shown in Figure 19.

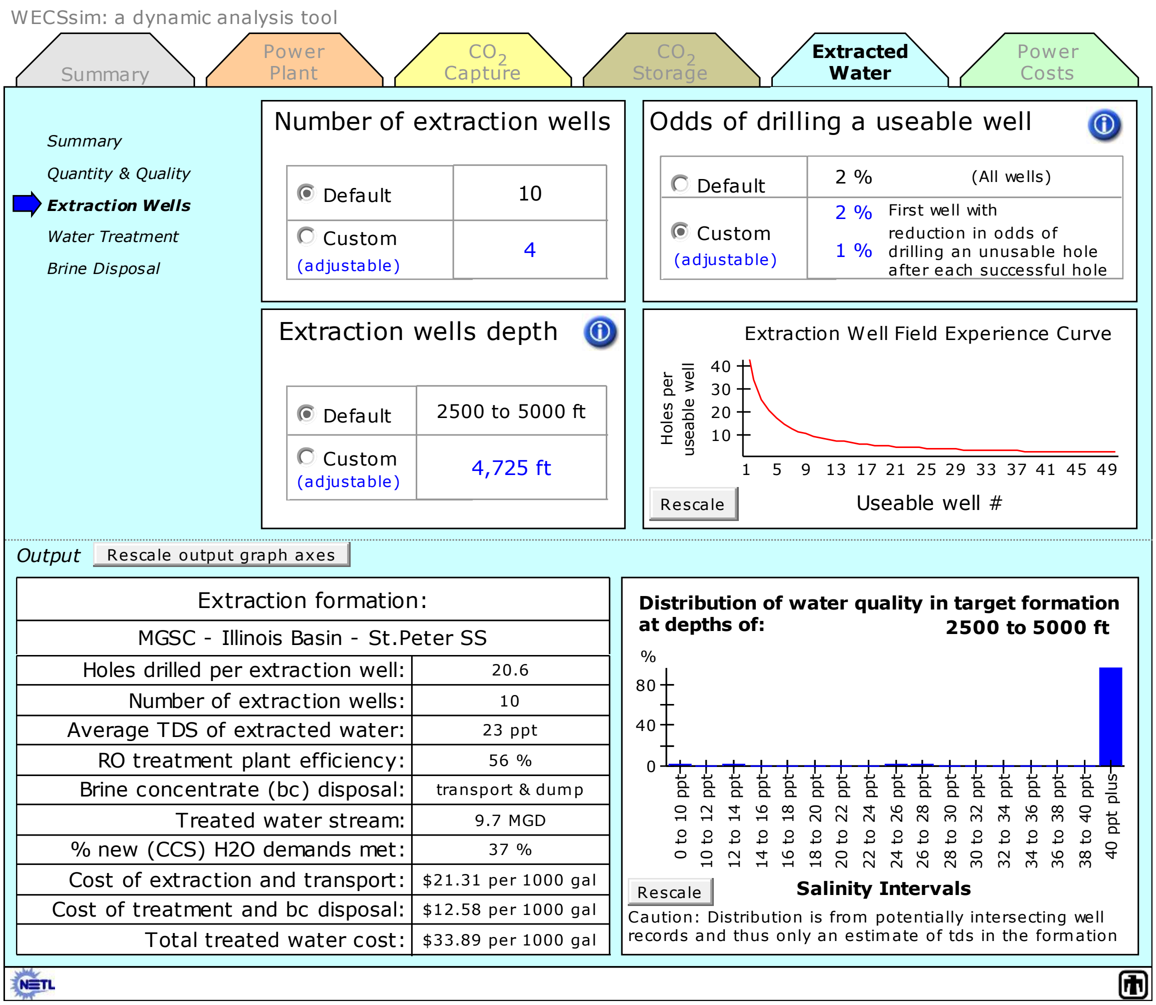

Figure 19. WECSsim Extracted Water – Extraction Wells Page.

Note: The custom alternative for calculation of probability of drilling a useable well has been selected, which changes the default results.

By default, this ratio is calculated as the number of well records with salinities in the target salinity range that are potentially intersecting the formation in a given depth range, divided by the total number of well records potentially intersecting the formation in that same depth range. For more information on potentially intersecting well analysis, see Appendix C. Alternatively, as seen in Figure 19, the user can specify a situation where as more wells are drilled, the chances of drilling a good well increase due to experience. Figure 19 shows that with a modest experience-based improvement in odds, the holes drilled per extraction well in this scenario decrease from around 42 to around 21, and treated water costs drop from $42.59 / 1000 gallons to $33.89 / 1000 gallons.

The same "useable bore hole" issue applies with injection wells on the low end of the water quality range where pore water is protected from CO_2 injection. Similar "useable well" options to those shown in Figure 19 for the Extracted Water module are available to the user in the Injection Wells page of the CO_2 Storage tab.

The Water Treatment page of the Extracted Water tab gives the user options to adjust parameters and assumptions associated with reverse osmosis plant efficiency and plant electricity usage costs. Additionally, Figure 20 illustrates the Brine Disposal page of the Extracted Water tab that gives additional user options to adjust select parameters for this subsystem.

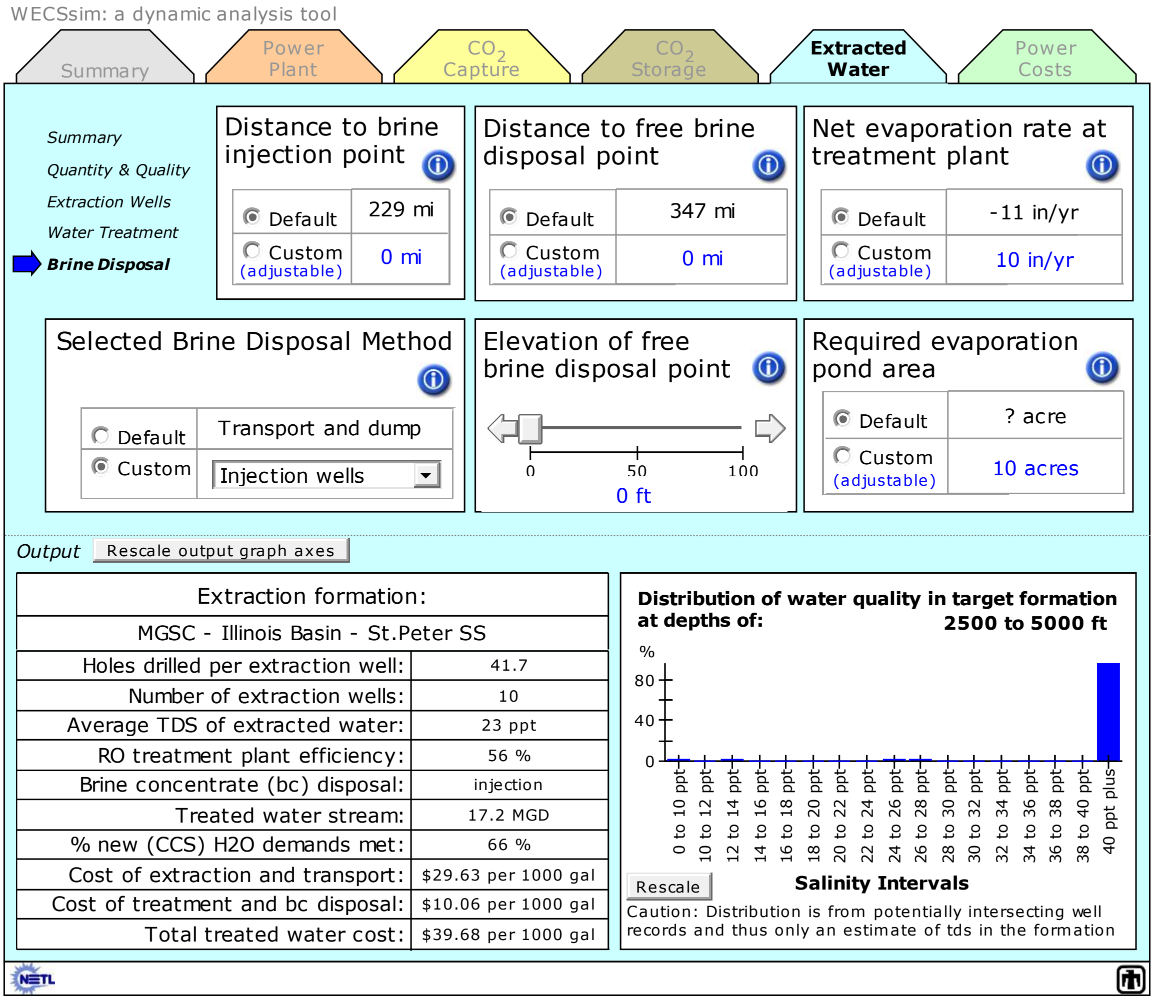

Figure 20. WECSsim Extracted Water – Brine Disposal Page.
Note: Injection wells have been selected for brine disposal resulting in changes to the default results.

Interestingly, in the John E. Amos default scenario considered here, WECSsim chooses to dispose of brine concentrate by piping it to the ocean, where it is assumed it can be disposed of at no cost.[3] For a power plant in West Virginia and a formation mostly under Illinois, this choice may be surprising at first. Options for brine concentrate disposal include evaporation, injection, piping to a location for free disposal (which is the ocean by default), or brine concentration with specialized equipment. Evaporation is not feasible in this scenario because the net evaporation rate (evaporation less precipitation) at the power plant is negative. That leaves brine concentration with specialized infrastructure, injection, or transport and dump. Why not

[3] This assumption may not hold true in many cases, and, as will be shown, this option can be overridden, or forced out of consideration with user input.

injection? Part of the answer is that in the injection–extraction case, WECSsim forces total volume out of the formation to be equal to total volume in.

If brine concentrate is to be reinjected, a sufficient amount of brine must be extracted so that the volume of brine extracted is equal to the volume of CO_2 injected *plus* the volume of brine concentrate reinjected. In this particular case, because the average salinity of extracted brine is fairly high at 23 ppt, the treatment plant efficiency is a modest 56%. This means that for every 100 gallons of brine treated, 56 gallons of treated water and 46 gallons of brine concentrate are produced. Thus, if the user selects “injection wells” as the brine disposal method as shown in Figure 20, the treated water stream jumps from 9.7 million gallons per day (MGD) to 17.2 MGD. Additionally, even though treated water costs drop from $42.59 to $39.68 per thousand gallons because the volume treated is nearly doubled, the overall costs associated with water extraction and treatment rise. For additional context, the specific LCOE water related costs rise from 0.80 to 1.32 ¢/kWh as seen on the Overview page of the Summary tab. Brine concentration with specialized equipment becomes the least expensive option for the John E. Amos power plant with default parameters if the reverse osmosis efficiency rises above 92%. This can be verified in the Water Treatment page of the Extracted Water tab.

Thus, the transport and dump option is often the cheapest option in WECSsim. To take the transport and dump option away so that WECSsim will choose the lowest cost option besides transport and dump, the user can specify on the Brine Disposal page of the Extracted Water tab (Figure 20) that the distance from the power plant to a free brine disposal point is thousands of miles. For the John E. Amos defaults, this results in WECSsim choosing the brine concentrator option, and total water costs rise from $42.59 to $48.05 per thousand gallons.

The calculations from the Power Plant, CO_2 Capture, CO_2 Storage, and Extracted Water modules all inform the Power Costs module as shown graphically in Figure 1. The next section discusses the Power Costs module interface.

7. POWER COSTS OPTIONS

The Summary page of the Power Costs tab is shown in Figure 21. The blue value in the table can be selected to enter a custom value. On the left-hand side of the screen, the specific sub-modules such as Base year & cap factors in Figure 21 take the users to another page. This page contains the assumptions underlying the specific set of parameters and they can be changed. The output shows costs of CO_2 capture and storage per mass stored or per mass of avoided emission depending on which option is selected with the radio button in the upper center of the output portion of the page. Unlike the other WECSsim modules, the Power Costs module is more of an integrating set of calculations where the assumptions can be changed, but is not the place to run a scenario. Scenario manipulations are performed in the Power Plant, CO_2 Capture, CO_2 Storage, and Extracted Water modules, while the Power Costs module exposes the underlying equations used to quantify the costs of each step. As a result, the Power Costs module can be used to understand the calculations that were made to quantify costs of each step of the CCS process.

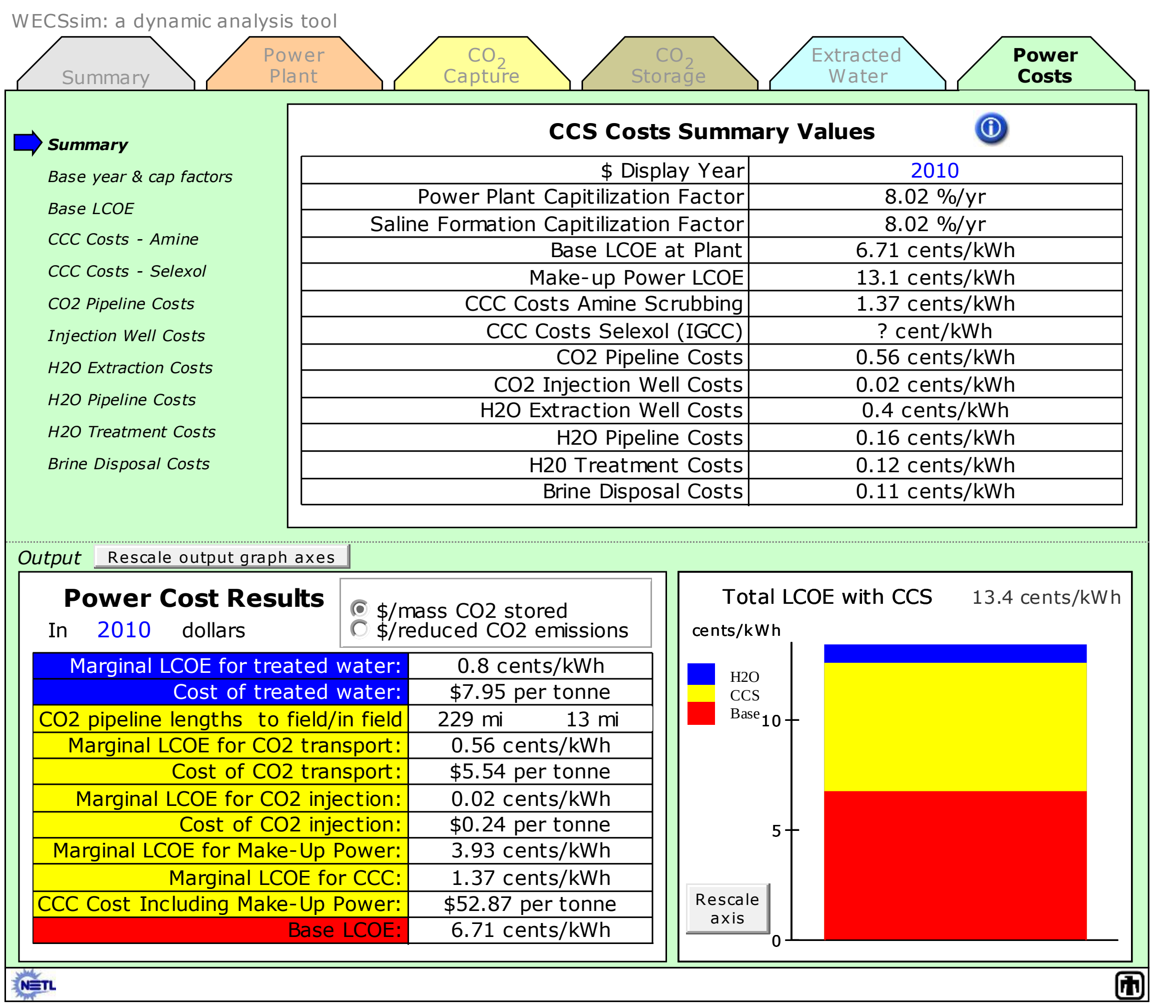

Figure 21. WECSsim Power Costs – Summary Page.

The Power Costs module rolls up the results from the different WECSsim modules, but to this point the manual outlined only the analysis of a single power plant.

8. FLEET ANALYSIS OF CO_2 CAPTURE AND STORAGE

In addition to a single power plant to various sinks matching capability, WECSsim has a fleet analysis mode that allows the user to evaluate CCS across the fleet of coal- and gas-fired power plants in the U.S. as represented by the eGRID 2007 power plant database (EPA, 2007). The WECSsim user interface changes in two ways in fleet analysis mode. Figure 22 shows the Overview page of the Summary tab where these changes can be seen. First, the ability to select a single power plant is removed. This ability impacts not only the Overview page of the Summary tab, but the Power Plant page of the Summary tab and the Summary page of the Power Plant tab as well. This compares to having power plant selection dropdowns available in the single plant analysis mode. Second, three additional options become available in the page menu of the Summary tab: Cost Curves, Water Curves, and Formation Use.

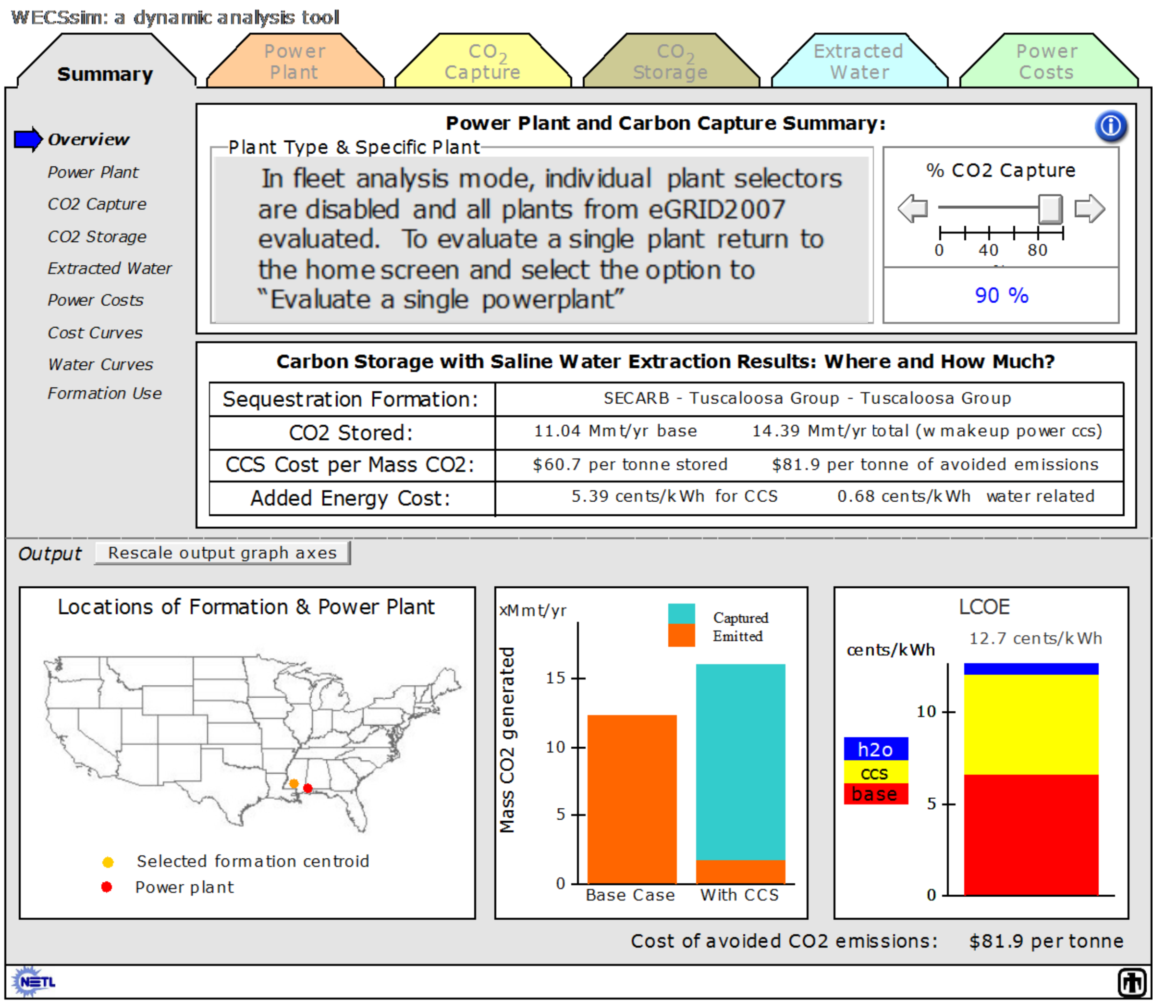

Figure 22. WECSsim Summary – Overview Page in fleet analysis mode.

Note: The power plant selection dropdowns visible in Figure 2a are not available, and there are three additional page options in the navigation structure at the top left, namely Cost Curves, Water Curves, and Formation Use.

To evaluate a scenario in fleet analysis mode, the user must run the simulation with the play button in the upper left portion of the screen. The play button is a blue triangle, see Appendix G. After pushing this button, the user will see WECSsim evaluate each power plant in the fleet. For the default scenario, 90% of CO_2 is captured at both the original and make-up power plant, make-up power is provided by the same power and cooling technology as the original power, brine is extracted and treated for use, power plants are not limited to using saline formations within a threshold distance, all storage formations are assumed to have closed boundaries, and there is competition between power plants for saline formations. These options all represent permanent defaults, meaning if the model user chooses to "Restore Permanent Variables" (see Appendix G), these values will be automatically selected.

For the fleet level analysis, a reference run is displayed as part of the selected output. Figure 23 shows the impact of forcing WECSsim to only select saline formations within 50 miles of the power plant. This change is made in the Sink ID & Location page of the Power Plant tab (Figure 11) by selecting the option to ignore formations greater than 50 miles away. This means that a

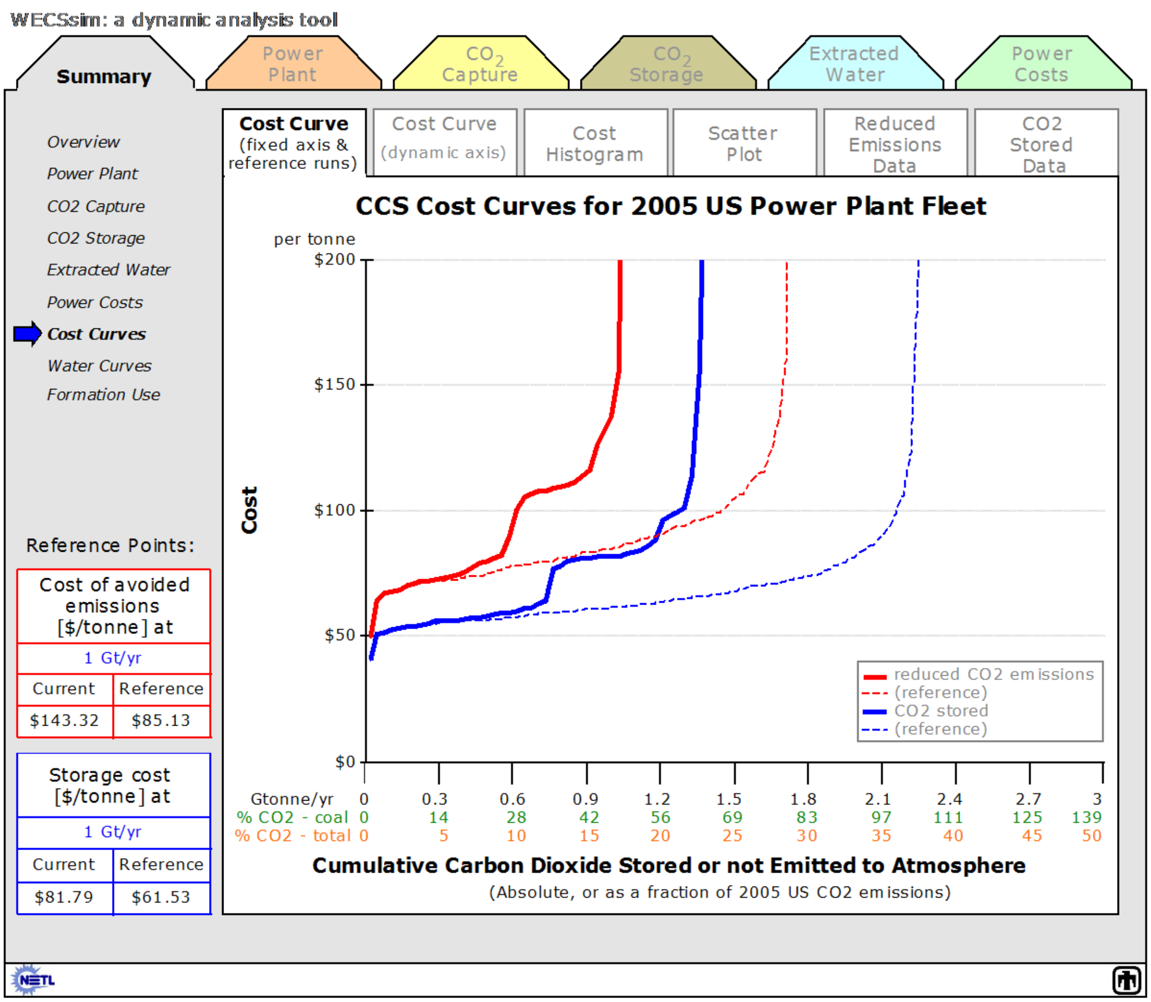

Figure 23. WECSsim Cost Curves.

Note: Scenario for which the power plant is limited to saline formations within 50 miles (solid lines) as compared to the base case run that does not have this limitation (dashed lines).

power plant's search function is restricted to those formations within 50 miles of it, rather than locating, explicitly, the least costly option for CO_2 storage and brine extraction. The cost curve shown in Figure 23 is developed by sorting the costs of storage or avoided emissions in ascending order, and then plotting them against the cumulative mass rate of storage or avoided emissions. The reference run is the fleet level base case described above and is represented by the dashed lines. The solid lines are for the scenario in which the power plant is limited to saline formations within 50 miles. The cost of storage or reduced emissions is higher with the forced distance restriction because certain plants are forced to settle on a more expensive option. The total amount stored or not avoided is less because some plants have no option at all within 50 miles. The reason the distance option is included in the model at all is to give the user the ability to simulate conditions under which political or legal constraints might limit long distance transport of CO_2 and or brine.

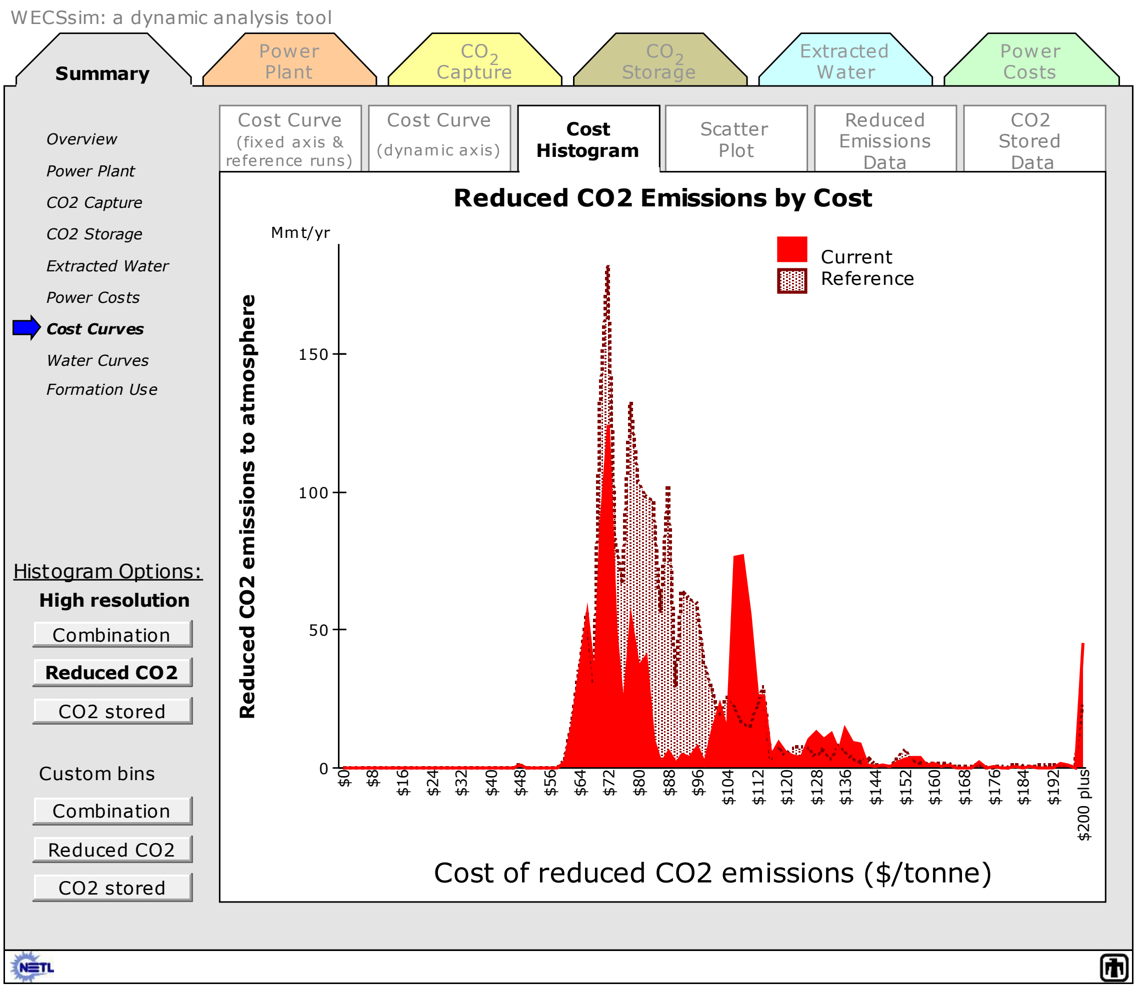

Figure 24. WECSsim Cost Histogram for Reduced CO_2 Emissions.
Note: For the scenario in which the power plant is limited to saline formations within 50 miles (Current) as compared to the base case run that does not have this limitation (Reference).

Figure 24 plots the reduced CO_2 emissions' costs versus reduced amounts of emissions in histogram form. It shows that the achievable amount of reduced CO_2 emissions for less than

$100 per tonne is much greater if no distance restriction is applied (Reference) than with the distance constraint (Current). The emissions spike around $108 per tonne in the distance restricted (Current) run represents power plants forced to use a more expensive option within the specified 50 mile distance, and is also seen in the hump in the cost curves in Figure 23. The Reduced CO_2 histogram is accessible from the interface in fleet analysis mode by clicking on Cost Curves, then clicking on the Cost Histogram tab at the top of the graphs, and then clicking on the Reduced CO_2 button in the Histogram Options list to the lower left. There are many options for visualization of the Cost Curves accessible to the model user by selecting the white tabs along the top of the output pane, and in some cases by additional selections in the vertical navigation menu in the lower left. (To see the navigation structure of all available pages in the Cost Curves portion of the fleet analysis interface, refer back to Figure 2b.)

Brine extraction can help mitigate pressure buildup and minimize areal extent of CO_2 in the storage formation used, as well as offset added water demands. However, it is expensive to extract, transport, and treat the brine. In the absence of competition for sinks, the available saline formation resource is very large for any given power plant. This is seen in Figure 25 where the

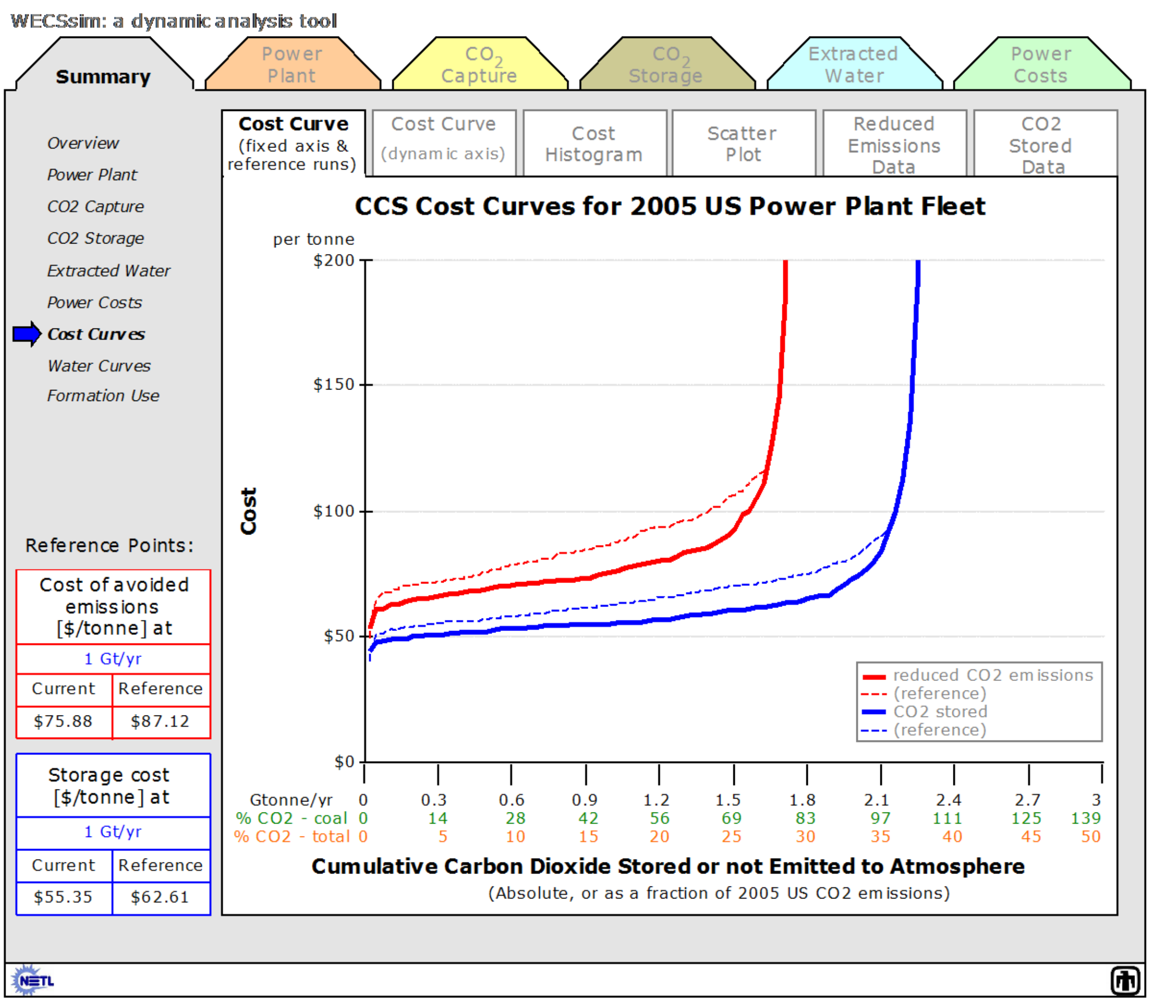

Figure 25. WECSsim Cost Curves for the base case without competition (reference) and base case without competition and without brine extraction (solid lines).
Note: Brine extraction and treatment increases the cost of CCS.

reference run is the base case without competition, and the current run is the base case without competition and without brine extraction.[4] These results do not include the benefit to the power plant of the added water source, nor do they include the benefits of reduced pressure buildup in the target formation. The benefit captured by WECSsim is to use less formation space and fewer injection wells. The formation space benefit can be seen by comparing fleet CCS costs with and without competition for sinks.

For the brine extraction case, there is no difference in costs between the scenarios presented with and without competition because the sink resource is used so efficiently (34–44% of pore space is occupied with CO_2. See Appendix F.) For the injection only case, however, fleet costs rise with competition for sinks making it more important to use the storage resource efficiently. Thus, with competition for sinks, extraction of brine becomes more compelling from a national perspective. Figure 26 shows the cost differences associated with extraction of brine when there is competition for storage space between power plants. Comparing Figure 26 to Figure 25 illustrates that the difference in costs between the brine extraction or no brine extraction scenarios narrowed.

[4] Competition for sinks means that once a power plant has selected a saline formation for CO_2 storage and calculated how much of that formation will be utilized during the lifetime of the injection and extraction well field, that portion of the saline formation is removed from the pool of available storage resources considered by the next power plant(s). The order in which the power plants are evaluated has some influence on the sink resources available to them, as the first plant has access to all potential sinks, and the last has access only to remaining sinks. This may influence CCS costs. The sorting order of the power plant to formation iterations is by power plant type first (e.g., pulverized coal, IGCC, etc.) according to states alphabetically. Future effort could be used to determine the order (e.g., alternate or random) in which power plants implement CCS.

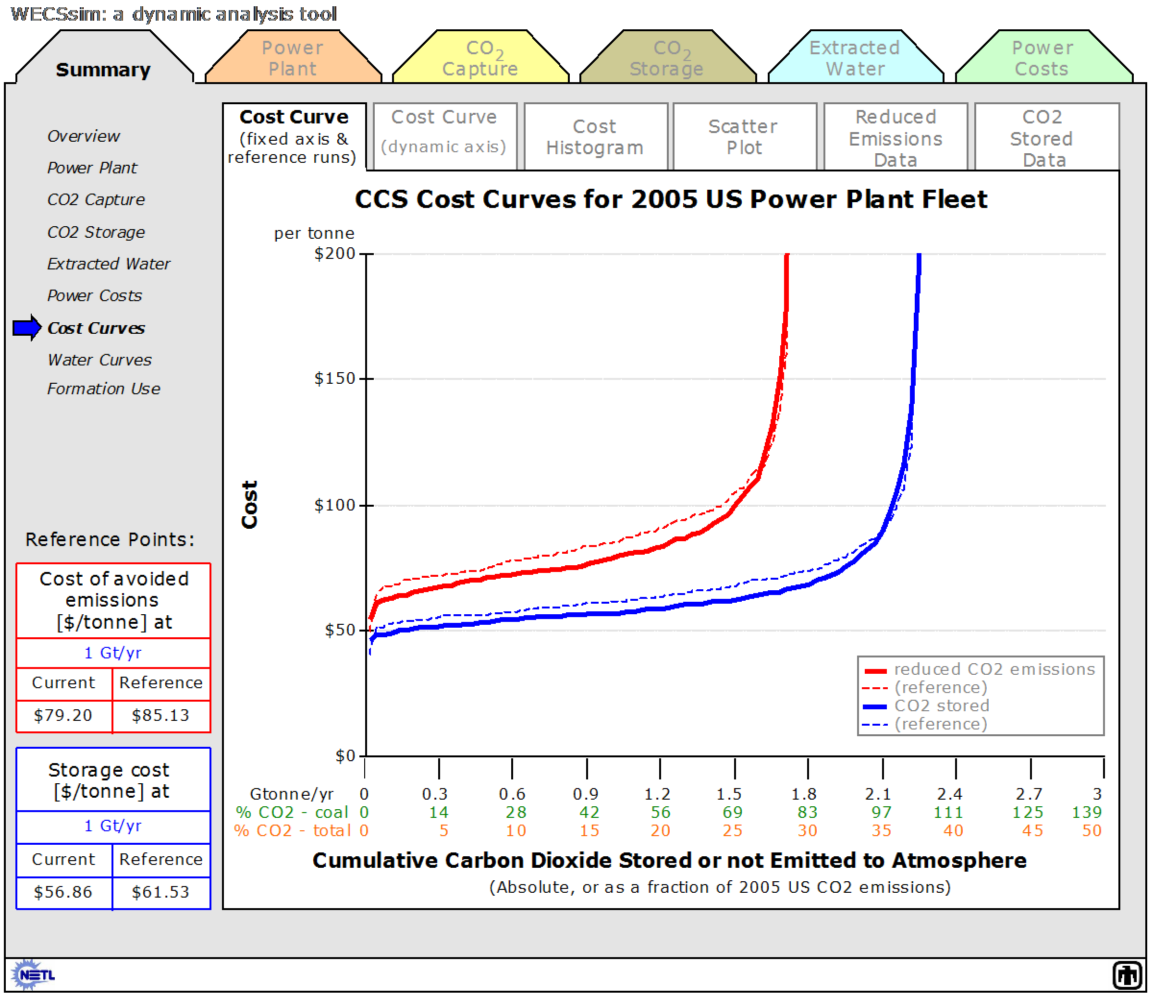

Figure 26. WECSsim Cost Curves for the base case (Reference) and base case without brine extraction (solid lines).

Note: Brine extraction and treatment increases the cost of CCS, but competition for sinks narrows the gap (compare to Figure 25).

The CO_2 storage efficiency advantage of simultaneous brine extraction with CO_2 injection as compared to injection only increases when competition develops or the size of the national geologic resource decreases. A simple way to simulate this effect with WECSsim is to specify that a power plant will secure geologic storage for more than the default 30 years. This parameter, called the “Well field design lifetime,” can be changed on the Injection Wells page of the CO_2 Storage tab shown in Figure 27.

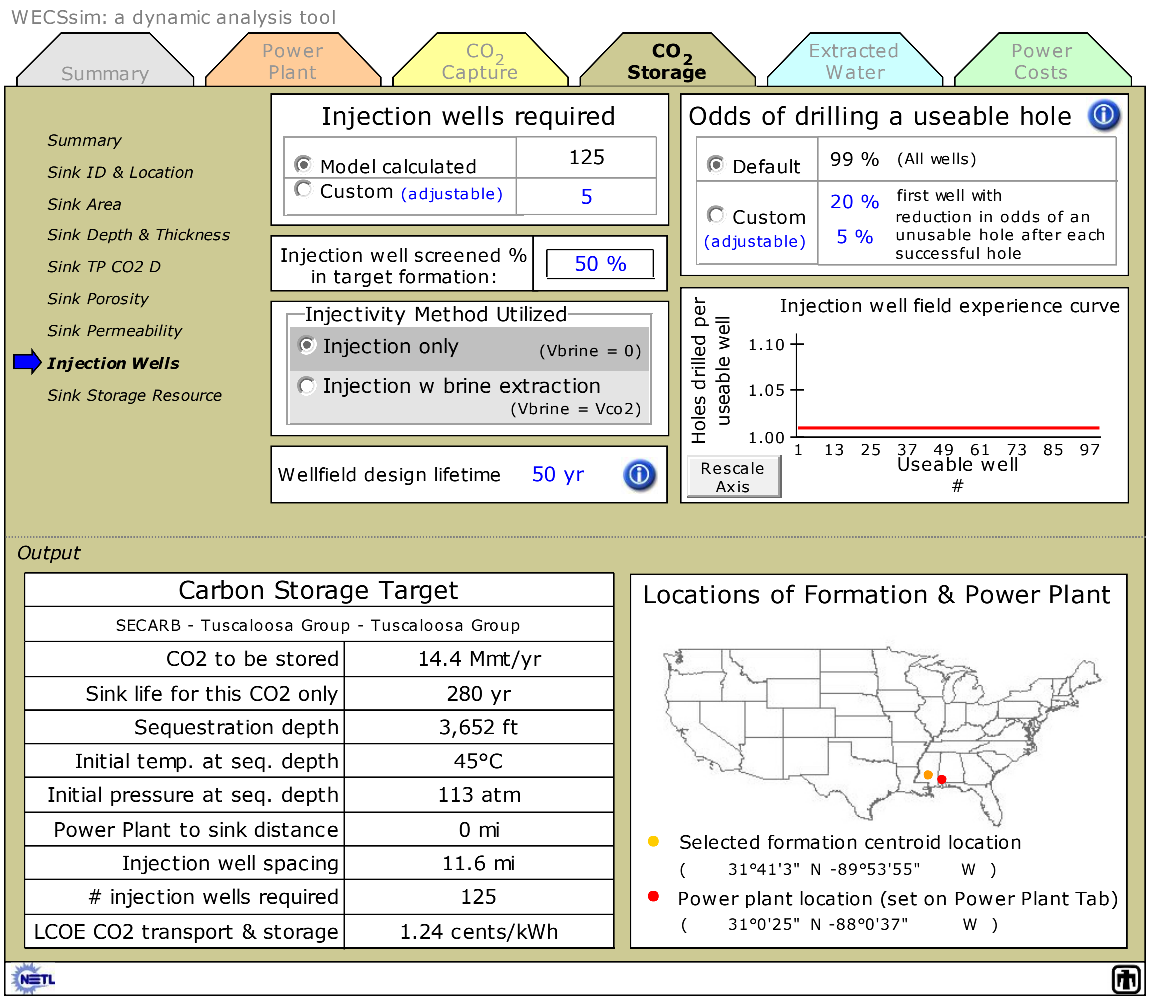

Figure 27. Injection Wells Page of CO_2 Storage Tab where the Well field design lifetime can be changed.

Note: In this case the well field design lifetime has been changed from a default value of 30 years to 50 years to test the effect of competition for a larger portion of the potential geologic storage resource.

The additional storage resource secured (50 years versus 30 years) makes no difference for the injection–extraction case because of the efficient use of the saline formations. However, as seen in Figure 28, it makes a substantial difference for the injection-only case where the formations are not used as efficiently. In this case, each power plant secures a larger portion of formation when CCS is implemented. The result is that injection only is slightly less costly up to approximately one gigatonne per year of avoided CO_2 emissions. Above this level of CO_2, the most cost-effective formations have been fully claimed, and the injection only case becomes more costly. The implications of this scenario are striking because they suggest that, from a fleet-wide perspective, extraction and treatment of brine during CO_2 storage may be economically preferable to injection-only case if the deep saline storage resource is slightly more limiting than assumed initially. Thus, if large scale CCS is to occur, brine extraction and treatment may play an important role in assuring that CO_2 storage in deep saline formations is a relatively cost-effective national solution in the decades to come.

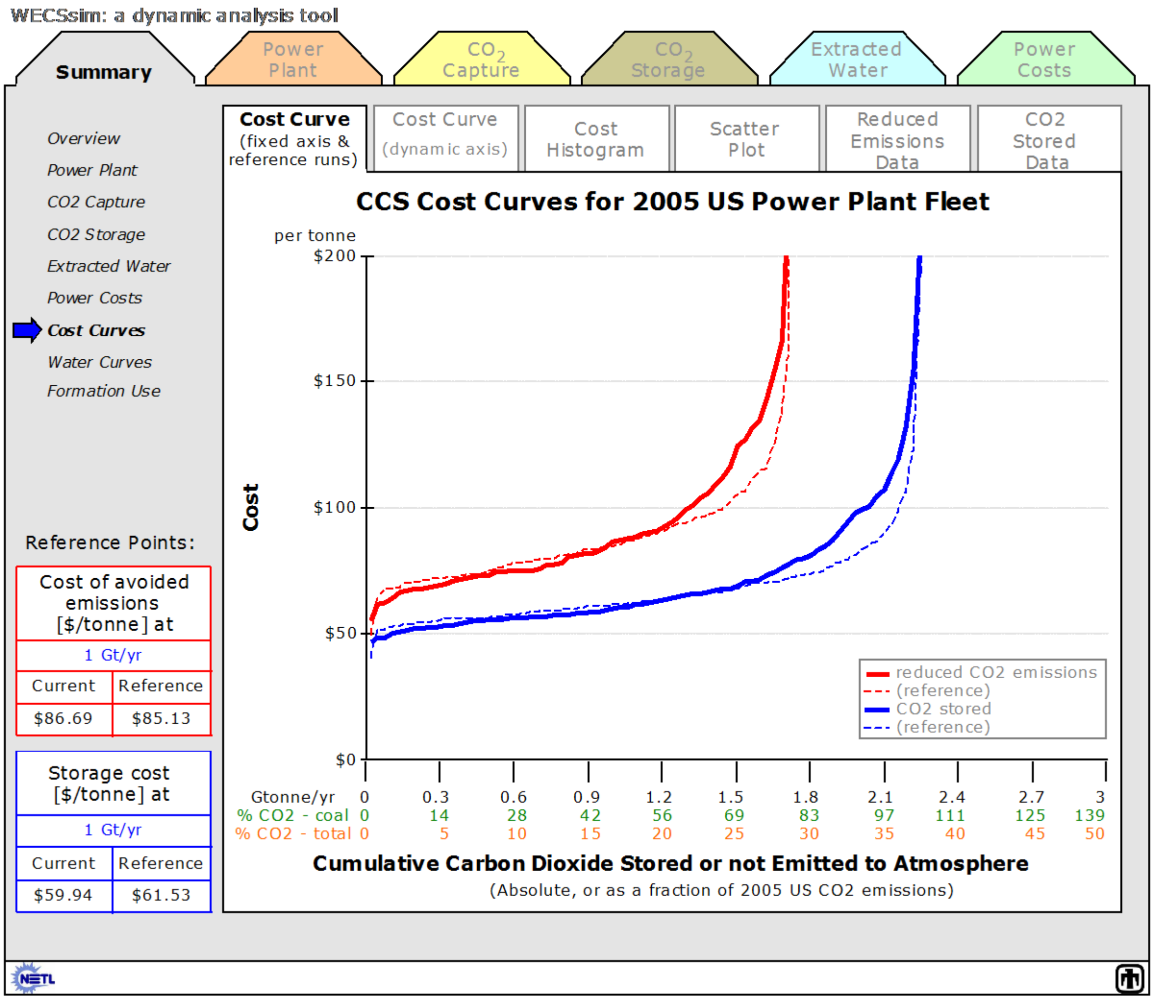

Figure 28. Injection only with competition for fifty years.

Note: Each power plant secures 50 years' worth of geologic storage when initiating CCS (solid lines) compared to the same scenario with simultaneous extraction of brine from the storage formation.

In addition to the cost curves described in Figure 28, WECSsim also displays water-use-specific data across the fleet of power plants evaluated for fleet runs. The page navigation structure on the Summary tab includes an option for Water Curves below the Cost Curves (See Figures 22–26 and 28). The model's display options include the cumulative added water demand and portion of that added demand offset by treated brine. (To see the navigation structure of all available pages in the Water Curves portion of the fleet analysis interface, refer back to Figure 2c.) To explore this output, an IGCC for make-up power (MUP) scenario was developed in Section 4. In addition to specifying IGCC as the MUP technology for all power plants, cooling towers are specified as the cooling technology for the MUP. (This is a change from the WECSsim default which sets MUP and MUP cooling technologies to be the same as utilized by the original plant.) These changes are made on the Make-up Power page of the CO_2 Capture tab as shown in Figure 29.

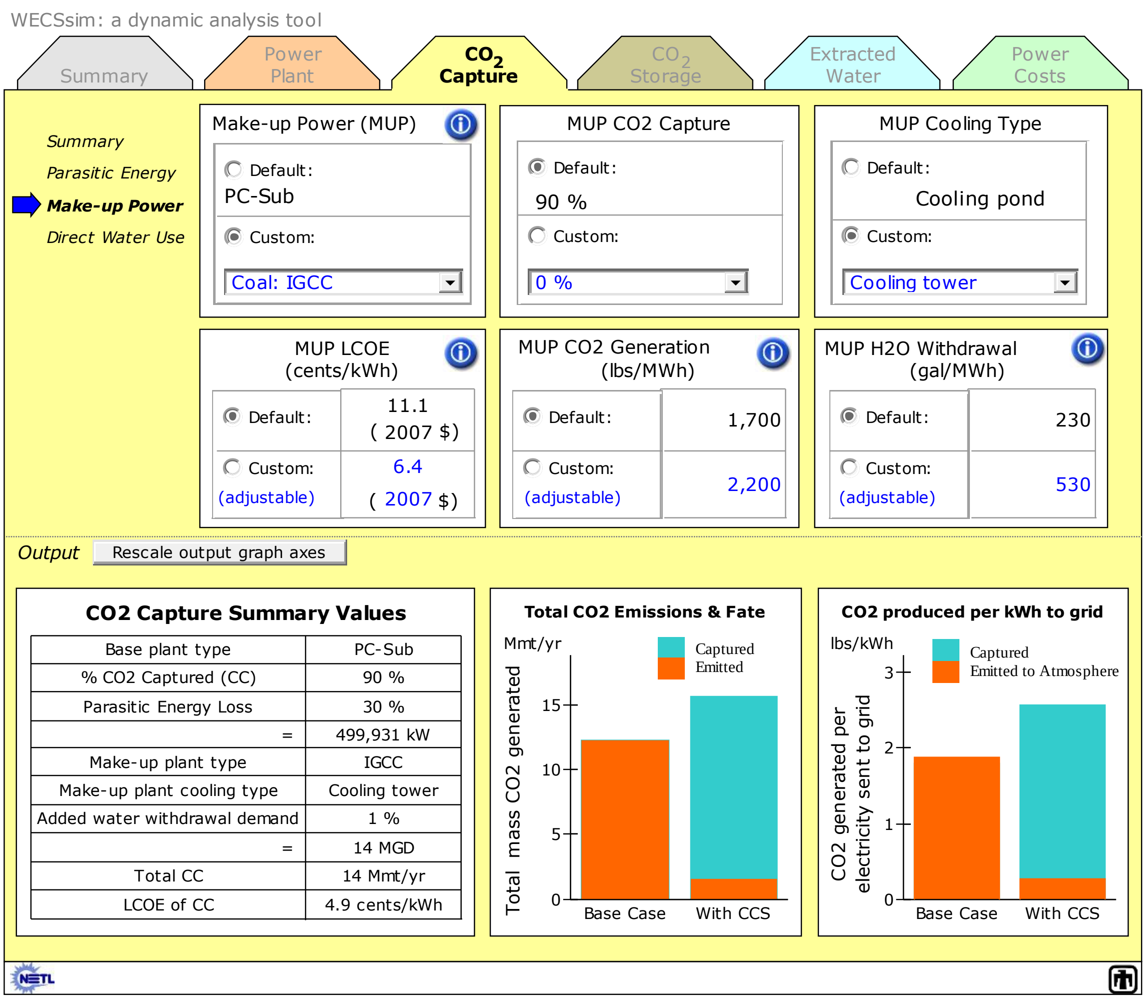

Figure 29. Scenario specifying IGCC with cooling towers for all make-up power.

The result of this change from a new water demands perspective is shown in Figure 30. The dashed lines are the default values. This scenario results in substantial reductions in new water demands associated with CCS, and as a result, the extracted brine offsets a larger portion of the new demands. For example, 1 gigatonne per year of reduced CO_2 emissions to the atmosphere adds only 1,278 MGD of new water demands if the system uses IGCC with cooling towers for MUP compared to 7,706 MGD for the base case (MUP plant is both of the same type as the original plant, and cooled with the same technology). At 1 gigatonne per year reduced CO_2 emissions, more than two thirds of the new demand (68%) can be offset with treated brine extracted from the formation as compared to only 12% for the base case scenario.

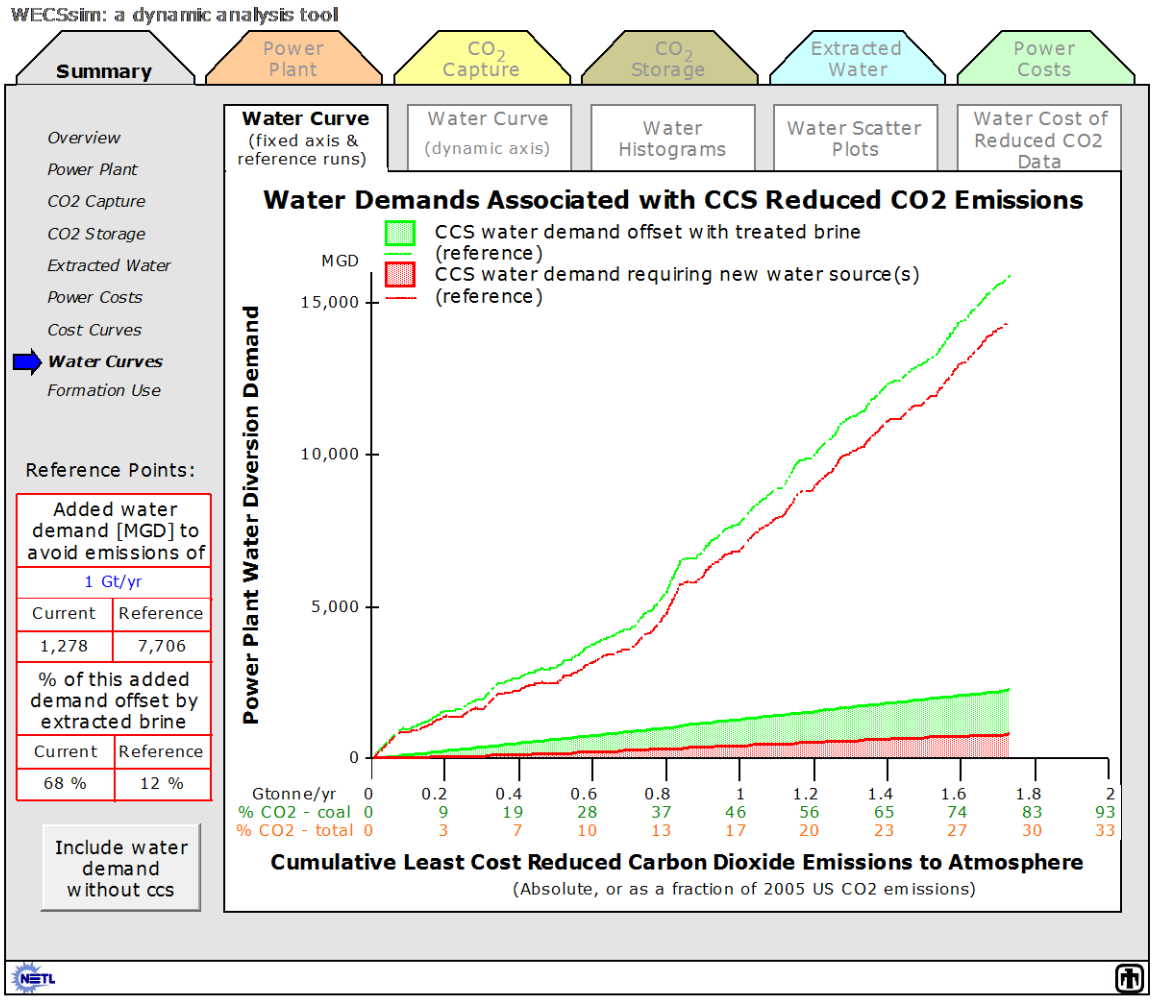

Figure 30. Added water demands (green line) and portion of those added demands met with treated brine from storage formation (green shading).

Note: This figure illustrates a reduction of CO_2 emissions to the atmosphere levels on the x-axis, whereas the dashed lines represent defaults.

The fleet level water use information can also be visualized in a histogram or via scatter plots. Figure 31 illustrates the high level histogram for the percent of added water demand offset by treated brine extracted from the storage reservoir at a given power plant. As can be seen from Figure 31, generating MUP with IGCC with cooling towers shifts the impact of treated brine on new water demands from small percentages to a situation where most CCS occurs at plants where more than half of the added water demand can be offset by water resources from the CO_2 storage target formation.

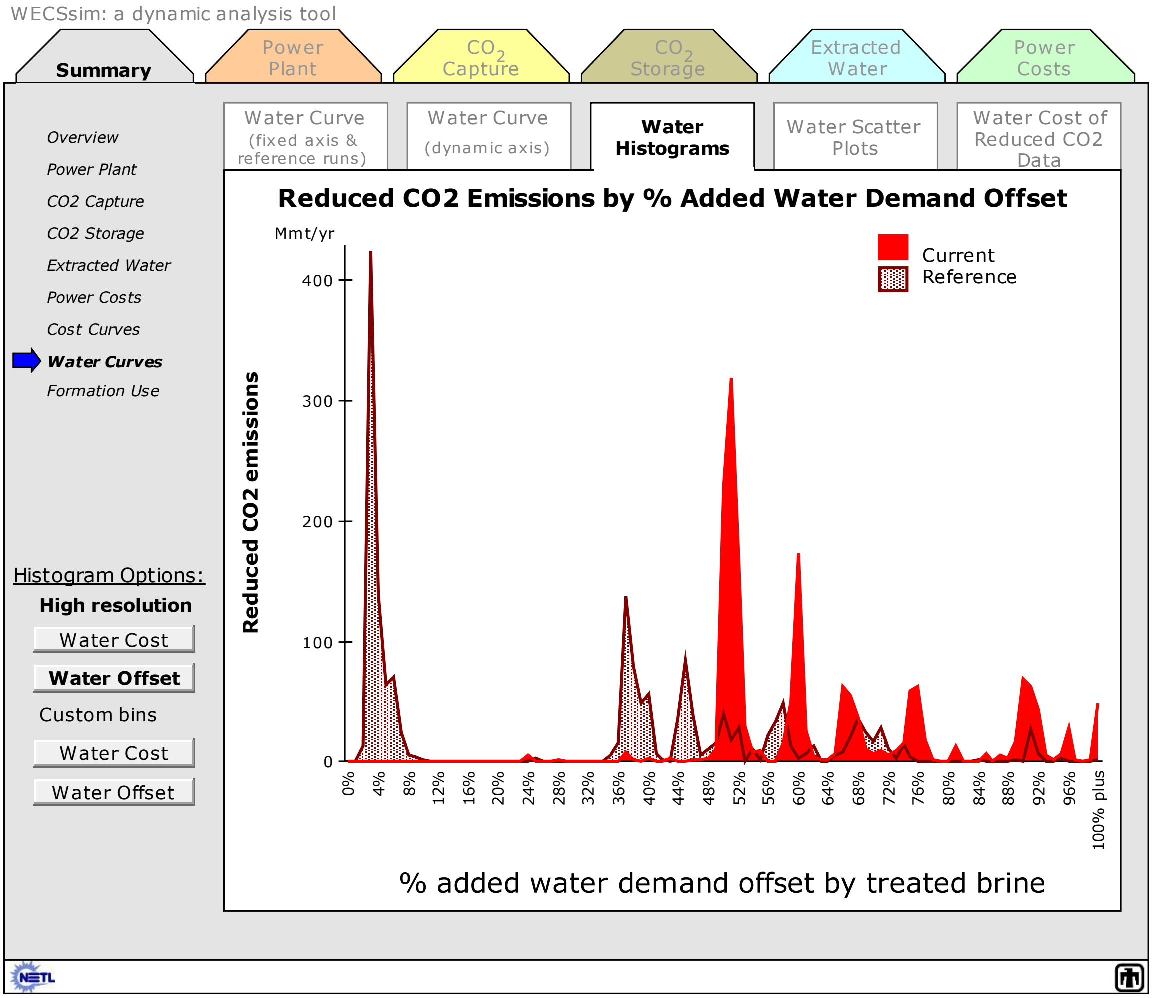

Figure 31. Histogram visualization of the percent of added water demand offset by treated brine from the CO_2 storage formation.

Note: The y-axis represents the amount of reduced emissions that were achieved at the power plant(s) where their added water demands were offset by the amount in the x-axis.

Clearly, utilizing IGCC with cooling towers is far more efficient from a water use perspective. As a result, the extracted and treated brine offers a substantial offset to the added water demands. As seen previously in Section 4, if CO_2 is to be captured from the MUP plant, IGCC is also the lowest cost option. Using IGCC for MUP as shown in this scenario reduces overall CCS costs. Thus, from both an overall cost and water use perspective, if CO_2 capture is to be included on the MUP plant, IGCC with cooling towers for all MUP plants is a preferred choice.

The third set of outputs associated with the fleet's analysis relates to overall formation use. The page navigation structure on the Summary tab includes an option for Formation Use below the Water Curves (See Figures 22–26 and 28). Options for display include formations used for a given reduction in CO_2 emissions, formation use histograms, specific information on the top formations used, and a dynamic map of source and utilized sink locations. (To see the navigation structure of all available pages in the Formation Use portion of the fleet analysis interface, refer back to Figure 2d.) To explore the Formation Use output, let us again consider the base case and the base case with no brine extraction scenarios. For these scenarios, the

Formation Use output makes it clear that a handful of formations in the U.S. would account for the majority of CO_2 storage. Specifically, the St. Peter Sandstone and Mount Simon Sandstone, both in the Illinois Basin, are by a sizable margin the most utilized sinks in the base case and scenarios with no brine extraction, respectively. Figure 32 shows the top formations for the base case (extraction of brine, competition for formations, and no distance constraint on power plant to formation pairing), and Figure 33 shows the top formations for the base case with no brine extraction.

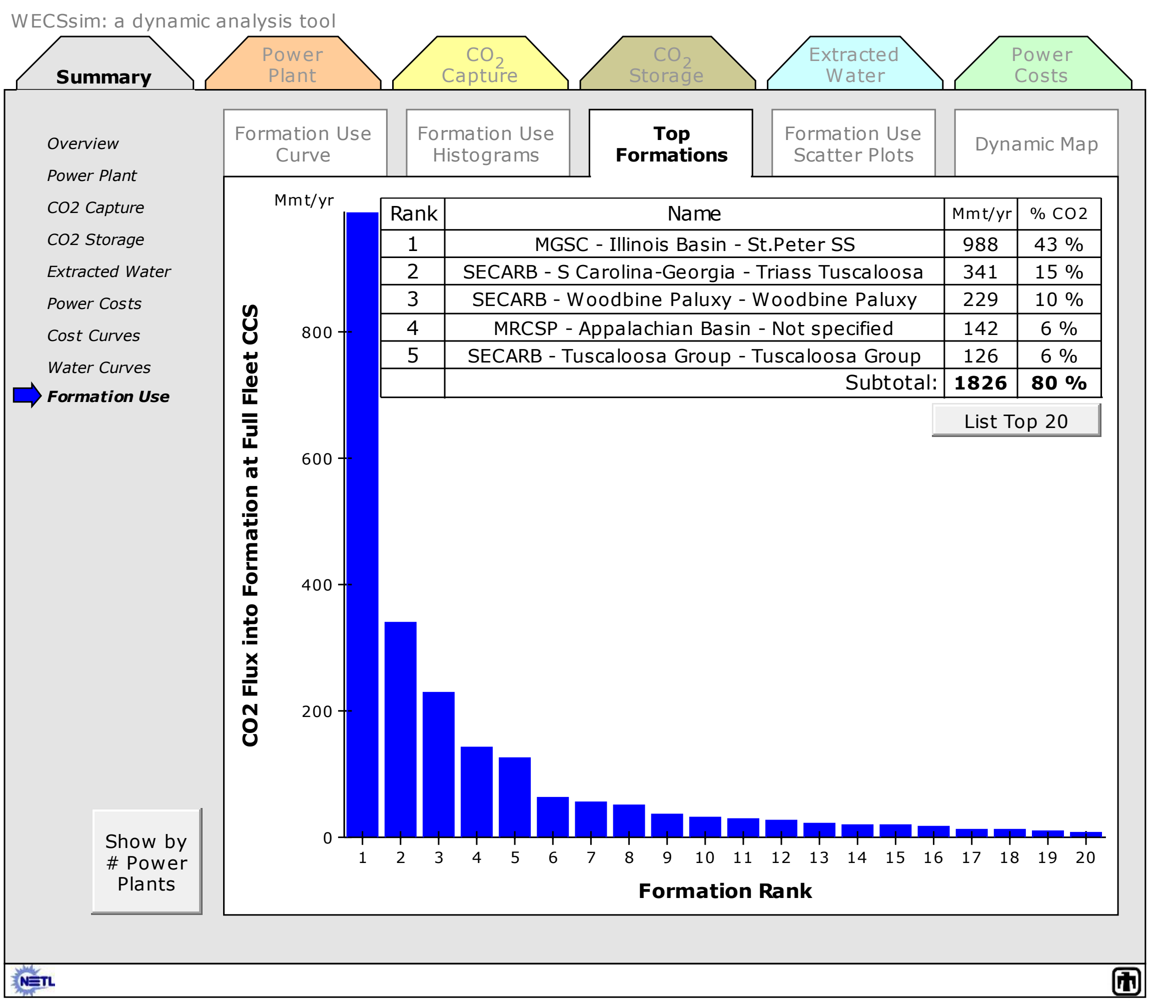

Figure 32. Top 20 CO_2 storage formations in terms of CO_2 stored for the base case scenario.

Note: The St. Peter Sandstone accounts for more than 40% of all CO_2 stored, and the top 5 formations account for more than 80% of all CO_2 stored.

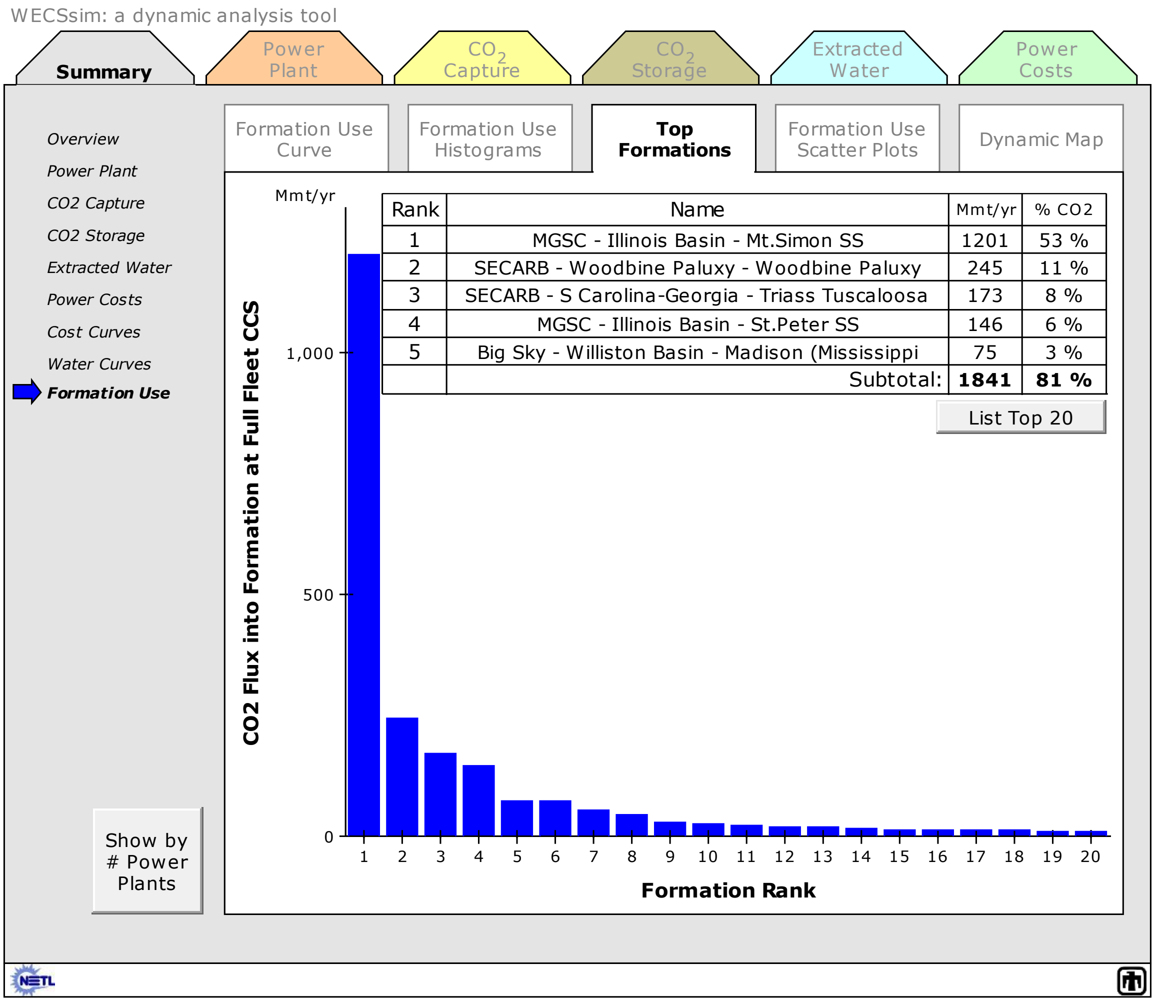

Figure 33. Top 20 CO_2 storage formations in terms of CO_2 stored for the base case with no brine extraction scenario.

Note: The Mount Simon Sandstone accounts for 55% of all CO_2 stored, and the top 5 formations account for almost 80% of all CO_2 stored.

The St. Peter Sandstone stores more than 40% of all CO_2 stored in the base case and nearly three times what is stored in the next most utilized formation. The Mount Simon Sandstone stores more than 50% of all CO_2 stored in the base case with no brine extraction and almost five times what is stored in the next most utilized formation. The St. Peter and Mount Simon Sandstones are well situated, relatively thick (169 feet and 1500 feet, respectively), large (76,000 km^2 and 143,000 km^2, respectively), and have relatively high mean permeability values (316 mD and 35 mD, respectively, compared to the WECSsim average of 33 mD). The Mount Simon Sandstone is the preferred of the two in the injection-only case because its large thickness and depth (allowing for a higher CO_2 density) reduces the spacing required between injection wells (3.1 km compared to 6.5 km for the St. Peter Sandstone). Thus, this substantially reduces the necessary surface piping. The reason the Mount Simon Sandstone is not utilized in the base case is because there are no potentially intersecting wells at the assumed depth of the Mount Simon Sandstone (7,121 feet) with TDS levels of less than 40,000 ppm. Thus, WECSsim cannot cost-effectively treat brine from this formation according to the current estimates of salinity in the formation and model assumptions of the range of practical treatment by reverse osmosis. As a result, when brine extraction is specified (base case), WECSsim chooses the St. Peter Sandstone instead of the Mount Simon Sandstone. The lack of water quality information in the Mount Simon Sandstone results in dramatic formation utilization differences in the brine extraction scenario. Thus, an improved representation of water quality distributions in the Mount Simon Sandstone should be a priority in data gathering to improve the analysis developed by WECSsim in the future. Due to the fact that only a few formations represent most of the CO_2 storage volume in the fleet (national-scale), scenarios suggest that future data gathering efforts should focus on the top five or 10 formations from these runs rather than all formations in the database. This is exactly the type of result for which WECSsim was designed, namely, a screening of all power plants and sinks to highlight those combinations that deserve a more detailed, site-specific analysis.

Figure 34 shows the Formation Utilization Curves, a representation of how many formations would be used at least once and how many would be fully utilized to achieve a lowest-cost reduction of CO_2 emissions to the atmosphere.

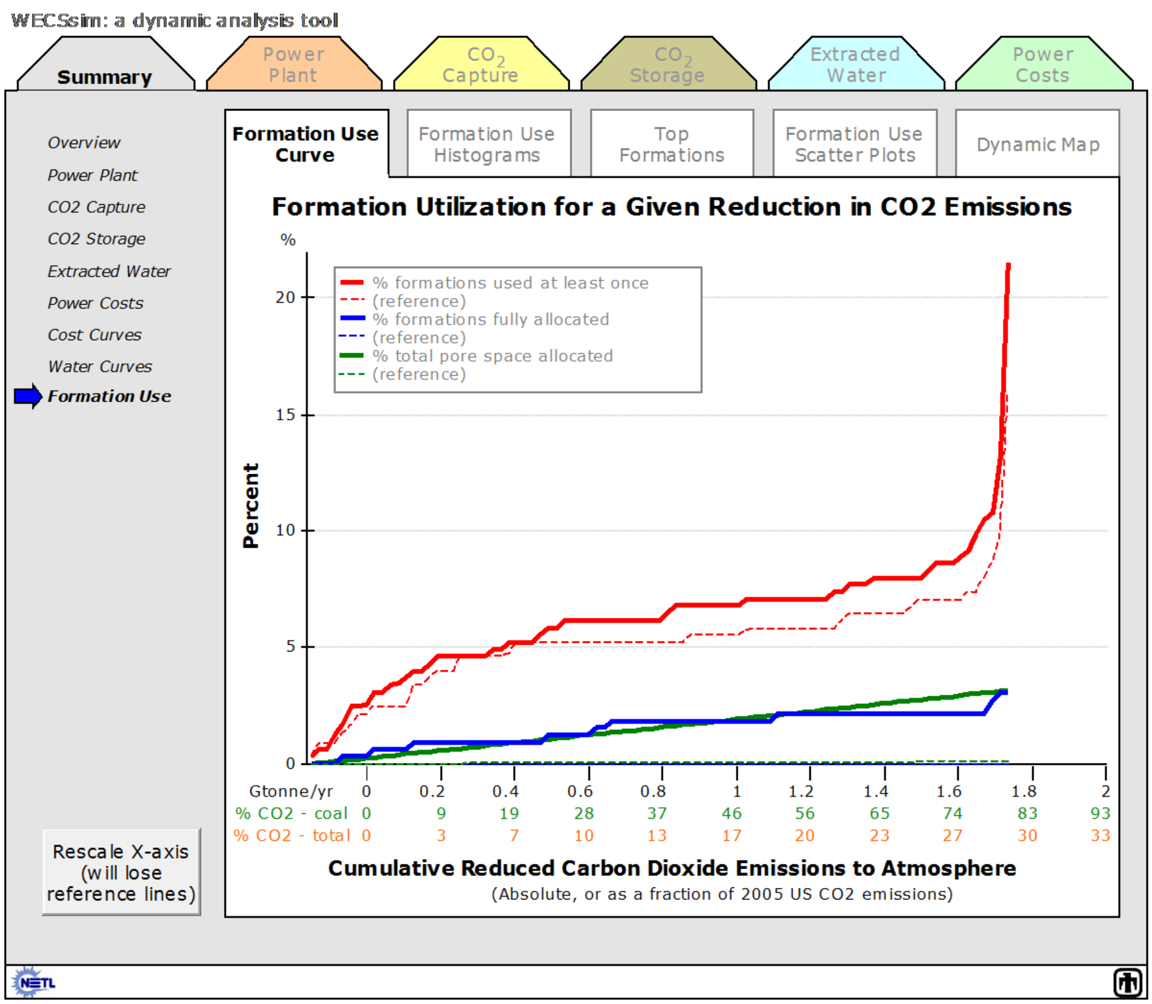

Figure 34. Formation use for the base case (dashed lines) and base case with no brine extraction (solid lines) scenarios.

Note: Without brine extraction more formations are used (red lines), and more formations are fully utilized (blue lines) because the pore space is being used far less efficiently than with brine extraction.

Figure 34 illustrates the injection-only case results in more formations being used and more formations used completely than does the injection with simultaneous brine extraction scenario. Once again, this is because the injection-only case utilizes the formations far less efficiently than injection with extraction. Figure 35a shows the Dynamic Map from the Formation Use output for the base case with injection only scenario. The large red circle in the bottom map of Figure 35a represents 800 or more Mmt/yr of CO_2 storage into the Mount Simon Sandstone, which is more than 75% utilized (see the legend in Figure 35b).

The fleet analysis output sections of the WECSsim interface, which include overall analysis of costs, water use, and formation use associated with national power plant fleet scale implementation of CCS provide a powerful set of tools to evaluate the implications of technology performance and cost scenarios. The myriad of insights available from WECSsim and these interface objects are open to the model user to fully explore.

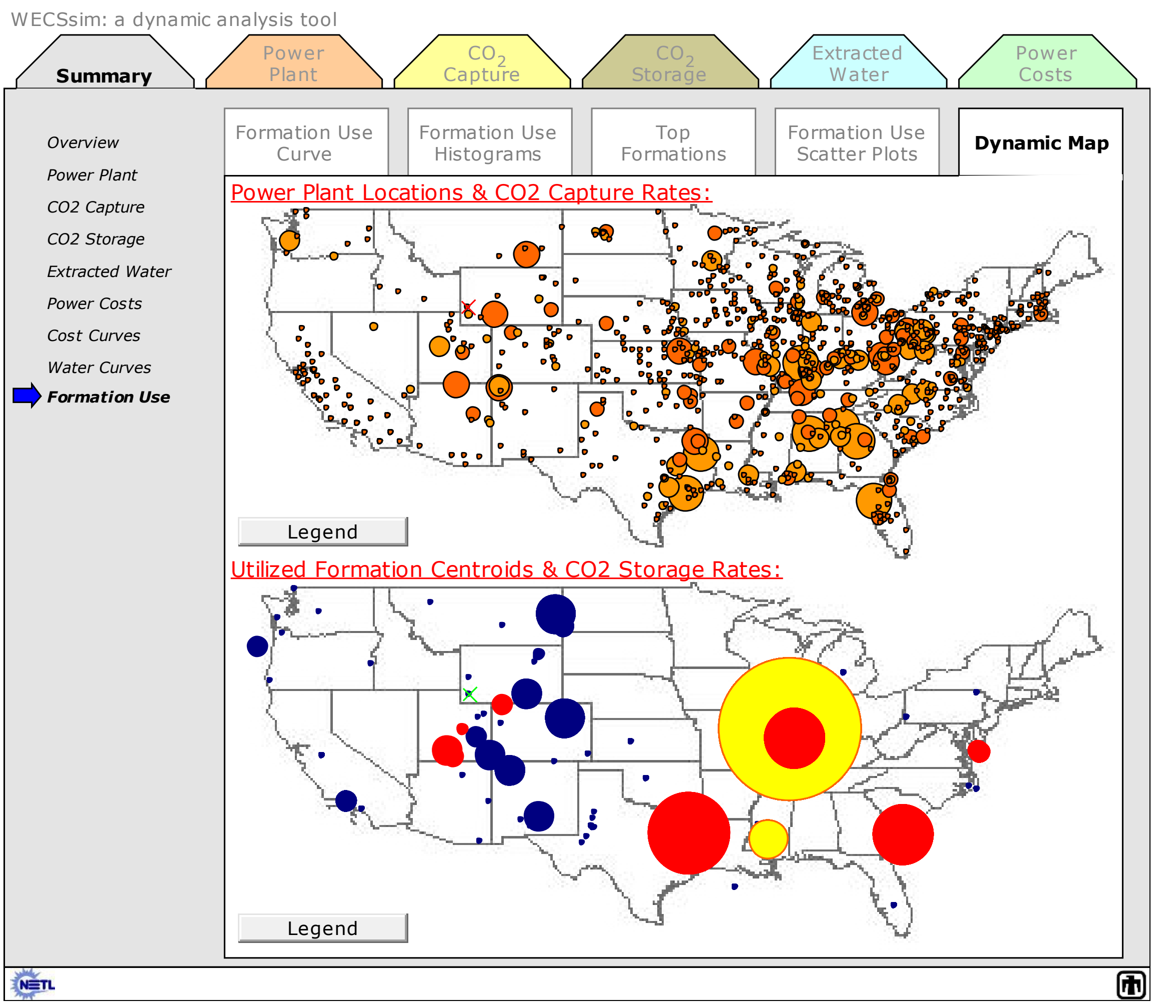

Figure 35a. Map of source and utilized sink locations and sizes for the base case with no brine extraction scenario.

Note: See Figure 35b for a legend. The largest yellow dot represents the Mount Simon Sandstone.

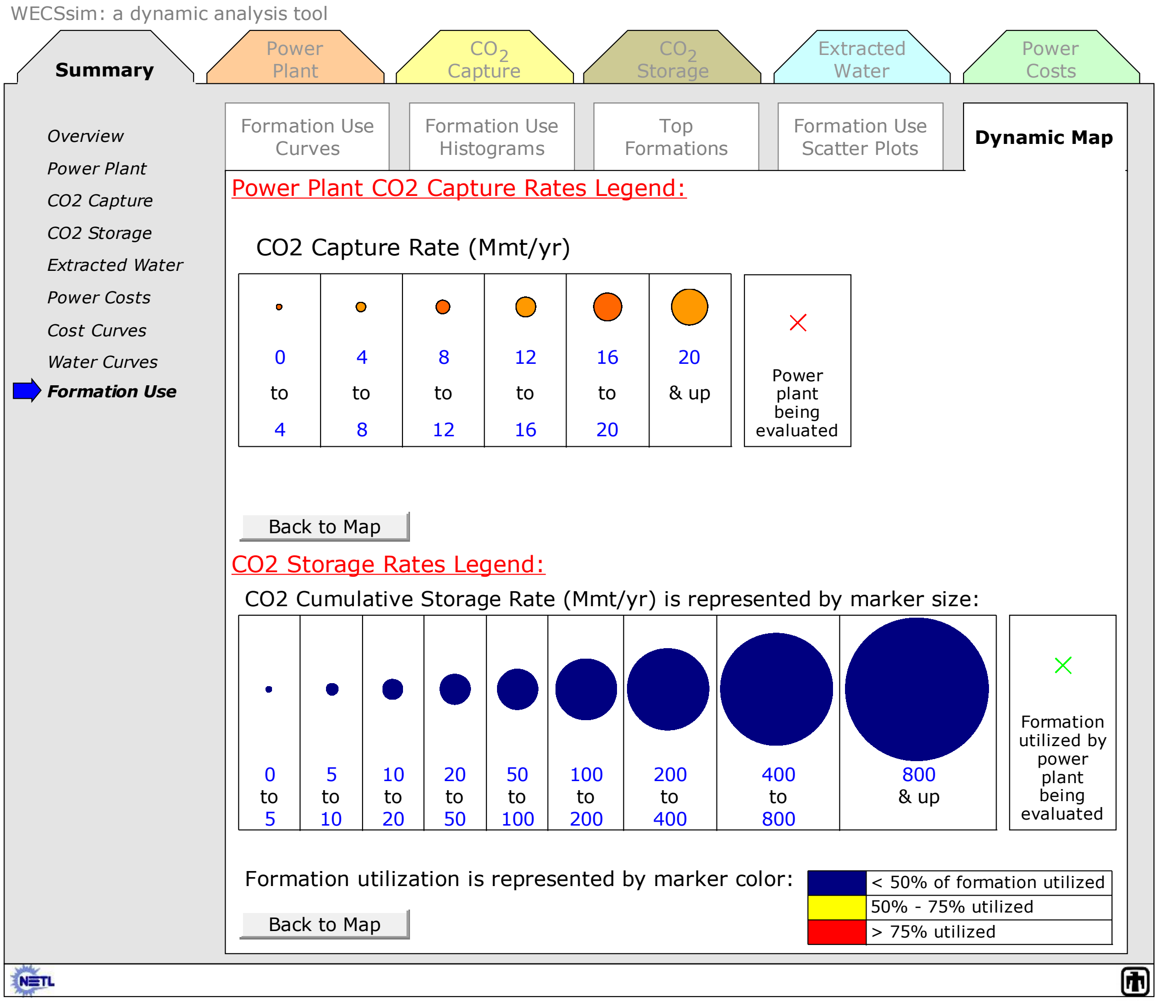

Figure 35b. Legend for markers on Dynamic Map of source and utilized sink locations and sizes.

9. DISCUSSION

The analysis presented in this report largely gives potential users of WECSsim the ability to understand the manner in which the model was developed, how to navigate it and some insights as to the sensitivities throughout the underlying scenarios that can be developed. With the user-friendly nature of WECSsim, as well as its flexible nature to develop custom power plant and fleet-wide scenarios, a wide range of cost, performance, and scoping analyses can be developed.

A few of the key parameters that influence WECSsim, roughly in order of importance, are the distance limit to store CO_2 in formations within 50 miles or beyond, the requirement to extract and treat saline formation waters (brine) or not, and the timescale under which the scenarios are run. The latter develops by extending the exclusive access rights of the power plant(s) to the saline formation's lifetime.

9.1 CCS Fleet Scenario Analysis Discussions

Previous analyses have shown that CO_2 capture costs represent the dominant cost in a CCS cost breakdown, but that estimates of financial, engineering, and geologic parameters can create substantial cost variability (Kobos et al., 2011a; Kobos et al., 2011b; Versteeg and Rubin, 2011; Heath et al., 2012; Kobos et al., 2012; Roach et al., 2012; Rubin, 2012). Additionally, the ability to scale up CO_2 capture, transportation, and storage infrastructure may be challenging in the near term due to both technical (engineering and geologic) and non-technical (permitting and energy-market-uncertainty) barriers (Nicot and Duncan, 2008; Michael et al., 2010; Herzog, 2011).[5]

Building off these previous, site-specific analyses, the scenarios developed in previous sections highlighted several WECSsim modeling capabilities. The following summary discussions illustrate how the model can be used to develop a series of comparative scenarios to more fully address questions such as:

- Will long transport distances between the power plants and saline formation sinks affect the costs and scale of the available storage resource?
- Will competition for the storage resource affect the costs and scale of the resource available to power plants? If so, within what timeframe?
- Will extracting H_2O from saline formations to alleviate pressure and space constraints increase the usable size of the storage resource? How will extracting water affect the system's costs?

Figure 36 illustrates a base case and three additional scenarios to address these questions. Cumulative rates of mass stored (blue lines) or mass not emitted to the atmosphere (red lines) are plotted as a function of ascending cost for all four scenarios.

[5] A brief scenario discussion highlights select CCS scenarios developed in previous sections (adapted from Kobos et al. (2012)).

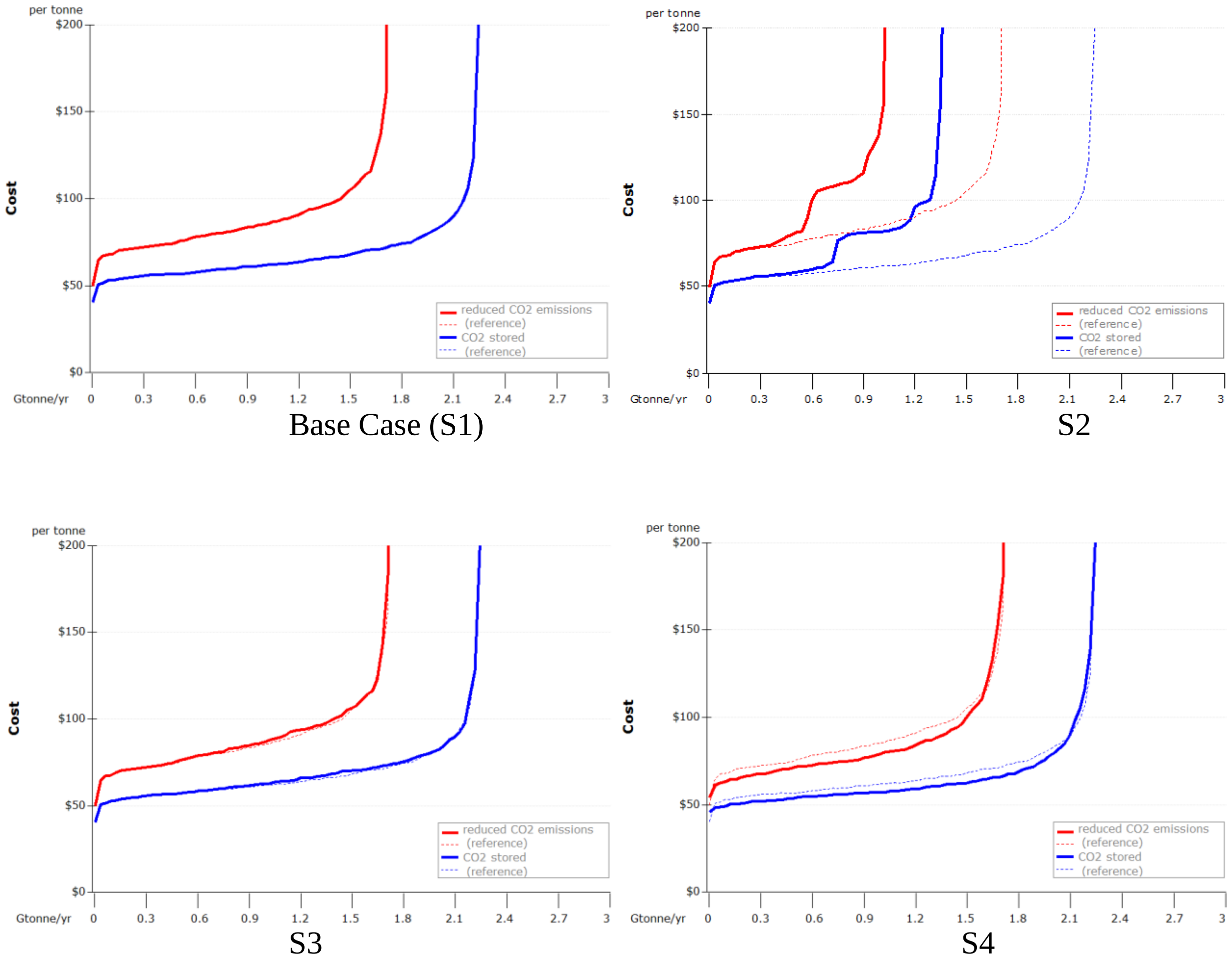

Figure 36. WECSsim results for the Base Case, 50 Mile, Competition, and Water Extraction Scenarios.

Note: Base Case, Scenario 1 (S1); Scenario 2 (S2), introducing a 50-mile limit between power plants and saline formation sinks for CO_2; Scenario 3 (S3), introducing no competition for sinks within the initial 30 years; Scenario 4 (S4), introducing no extraction for saline waters, rather, only injecting CO_2 at the saline formations.[6]

The base case scenario (S1) evaluates power plants that are not constrained by any distance limit to potential storage sinks, they compete with the rest of the power plant fleet for CO_2 storage space for an initial 30-yr period, and they extract H_2O while injecting CO_2. Scenario 2 (S2), limits the power plants to use sinks within 50 miles. Scenario 2 was developed to account for potential legal issues included with the assumption that the water extracted from saline formations is to be piped back to the original power plant. Factors not modeled explicitly such as the ability to move water legally across state lines and other rights considerations may limit the ability to move water back from a power plant's chosen CO_2 saline formation sink. Scenario

[6] **Scenarios with 30 year sink rights:**
Base Case, Scenario 1 (BC, S1): No distance limit; competition for sinks; extract H_2O; 30-yr well lifetime & sink rights
Scenario 2 (S2): *50-mile distance limit*; competition for sinks; extract H_2O; 30-yr well lifetime & sink rights
Scenario 3 (S3): No distance limit; *no competition for sinks*; extract H_2O; 30-yr well lifetime & sink rights
Scenario 4 (S4): No distance limit; competition for sinks; *do not extract* H_2O; 30-yr well lifetime & sink rights

3 (S3) presents a case where there is no direct competition between power plants for space in the saline formations to store CO_2. Scenario 4 (S4) compares a situation where no saline water is extracted while power plants are injecting CO_2 into saline formations.

Comparing Scenarios 1 and 2, the costs dramatically increase for the avoided (and stored) cost for CO_2 when changing from an unconstrained distance between the plants and sinks (S1) and a 50-mile maximum distance between the plants and sinks (S2). Another key point between S1 and S2 is to note the Avoided Costs of 1 Gtonne/yr emissions (Table 1) are almost doubled when restricting the sinks to within 50 miles of the plants, and the total potential reduced CO_2 emissions are reduced to almost half (Figure 2, S2). This speaks to the point that allowing the model the freedom to calculate the most economical solution by not imposing an arbitrary source-to-sink distance constraint results in more avoided emissions per dollar invested.

Relaxing another constraint to now avoid competition between power plants for a given sink, one compares S1 and S3. The supply curves are very similar because brine extraction results in very efficient use of the pore space such that it does not appreciably limit the storage resource even for fleet-wide competition. This is due to the fact that the effects of the distance constraint seen when comparing S1 and S2 far exceed the influence of power plants competing for sink space when comparing S1 and S3 within an initial 30-yr time period.

Another option is to not extract the saline waters while injecting CO_2 at the saline formations. By not extracting saline waters, the costs fall modestly across the sink options as seen by comparing S1 and S4. Overall system's costs are lower because brine is no longer being extracted and desalinated to use as cooling water; however, these costs are not as low as they would be in the absence of competition. Forgoing brine extraction reduces costs but increases the effect of competition because of the less efficient use of the pore space. In S4, there are sufficient storage volumes available for 30 years where, even with fleet competition for the storage resource, the cost savings outweigh the less efficient use of storage volume resulting from not extracting H_2O. However, this balance is sensitive to the assumed well field lifetime.

Figure 37 illustrates both the avoided costs and storage costs corresponding to Scenarios S1 through S4 to give a sense of the variability in costs up to \$200 / tonne CO_2 and beyond.

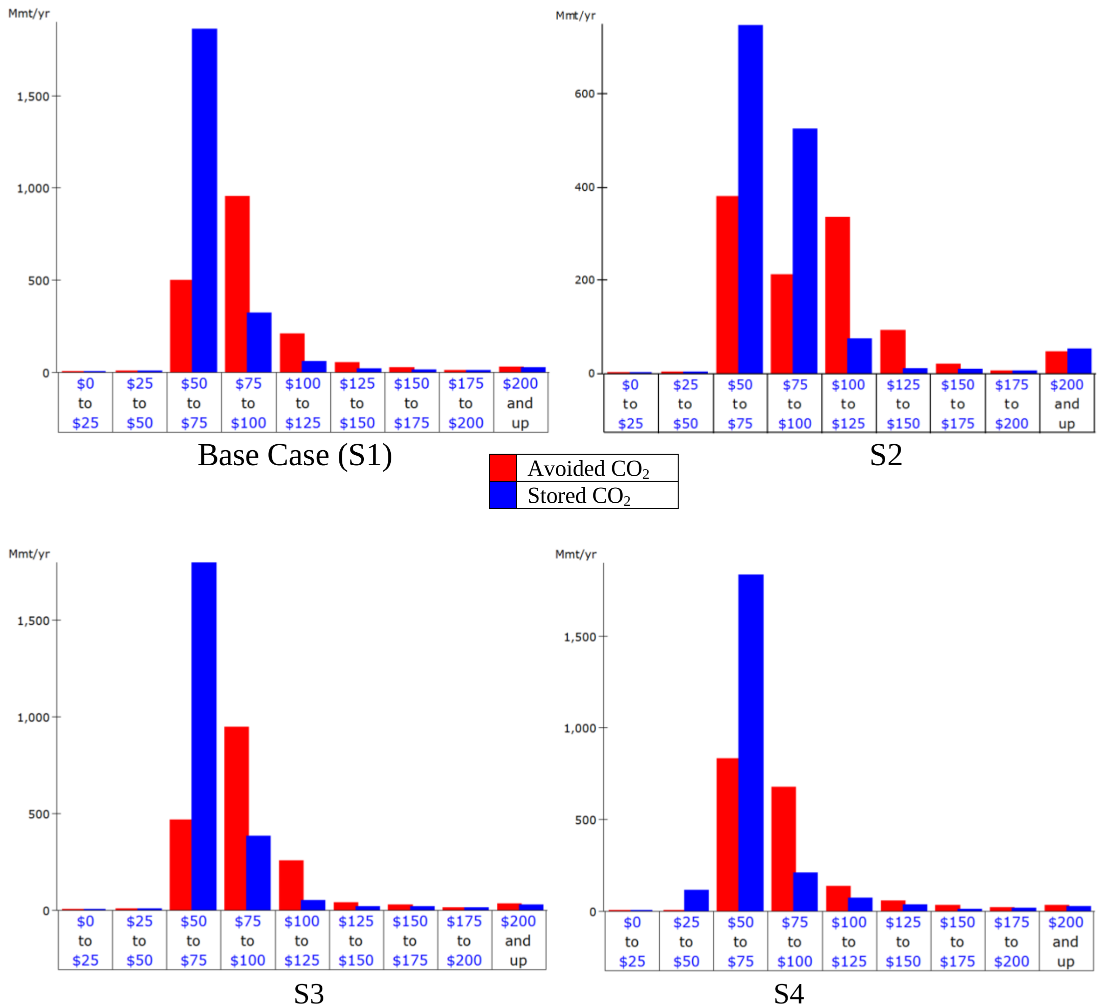

Figure 37. WECSsim scenarios for the Avoided and Stored CO_2 costs.

Note: Scenarios 1 through 4 illustrating the base case, option to limit source-to-sink distances to 50 miles or less (S2), option to introduce competition between power plants for sink storage space for 30 years, and the option to not extract H_2O while also injecting CO_2.

To address the somewhat limited changes in the Scenario 4 results (with competition for storage space), an additional set of scenarios was developed. These scenarios have a longer timeframe for the power plants to lay claim to storage space in the face of competition for low-cost saline formation storage options. Scenarios 5 through 8 illustrate a similar set of constraints regarding a 50-mile limit, competition for storage space, and exercising the option to extract H_2O or not, while giving power plants up to 60 years of rights for space they may need to store CO_2 instead of 30 years (see Figure 38).

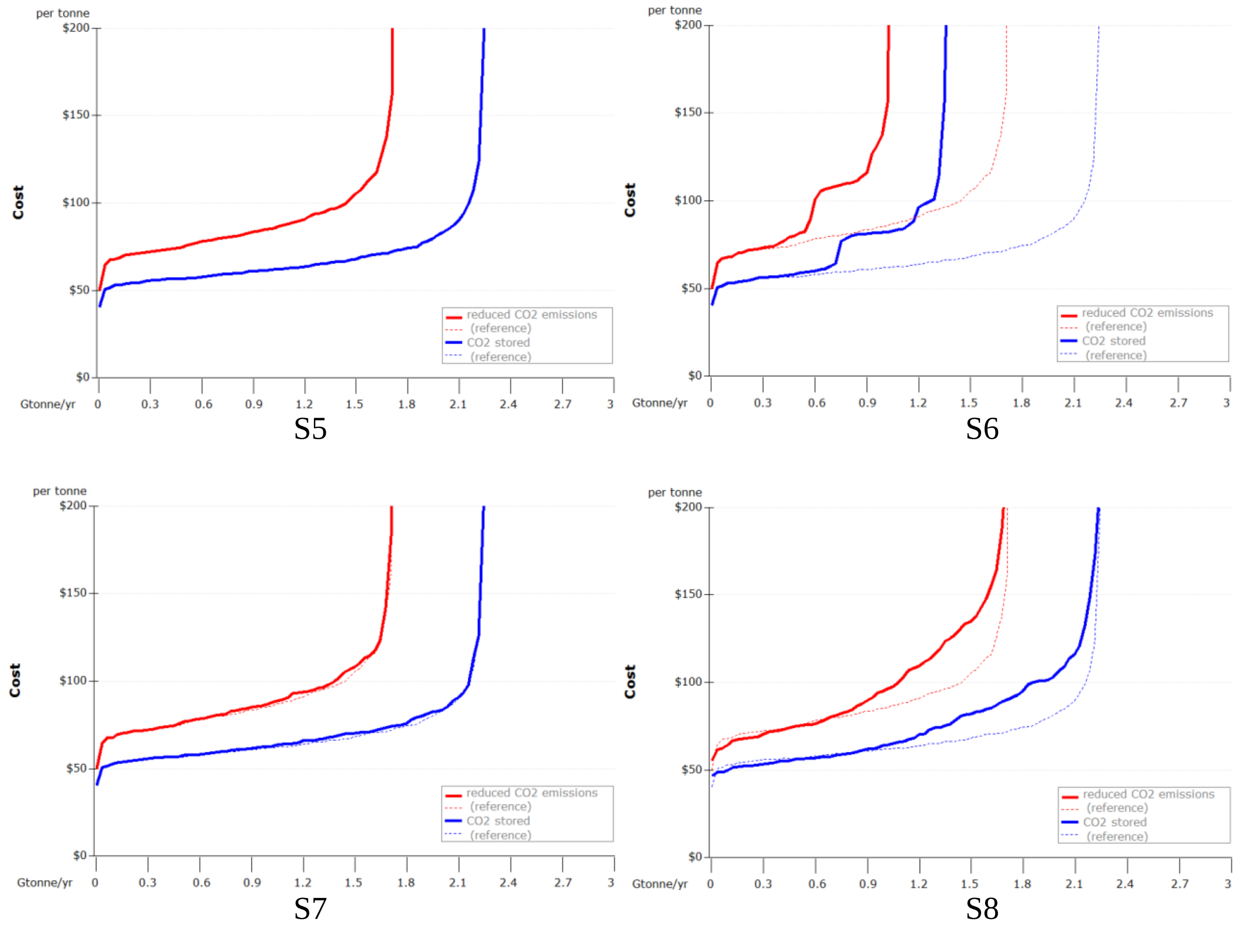

Figure 38. WECSsim scenario results while including a 60 year claim to storage space. *Note: Scenario 5 (S5) introduces a 60-yr claim to storage space rights per power plant for scenarios 5 through 8 under the competition option; Scenario 6 (S6) introduces a 50-mile limit between power plants and saline formation sinks for CO_2; Scenario 7 (S7) introduces no competition for sinks within the initial 60 years; Scenario 8 (S8) introduces no extraction for saline waters, rather, only injecting CO_2 at the saline formations.*[7]

Figure 39 illustrates the storage and cost (avoided and storage) details corresponding to Figure 38.

[7] **Scenarios with 60 year sink rights:**
Scenario 5 (S5): No distance limit; competition for sinks; extract H_2O; 60-yr well lifetime & sink rights
Scenario 6 (S6): *50-mile limit*; competition for sinks; extract H_2O; 60-yr well lifetime & sink rights
Scenario 7 (S7): No distance limit; *No competition for sinks*; extract H_2O; 60-yr well lifetime & sink rights
Scenario 8 (S6): No distance limit; competition for sinks; *do not extract H_2O*; 60-yr well lifetime & sink rights

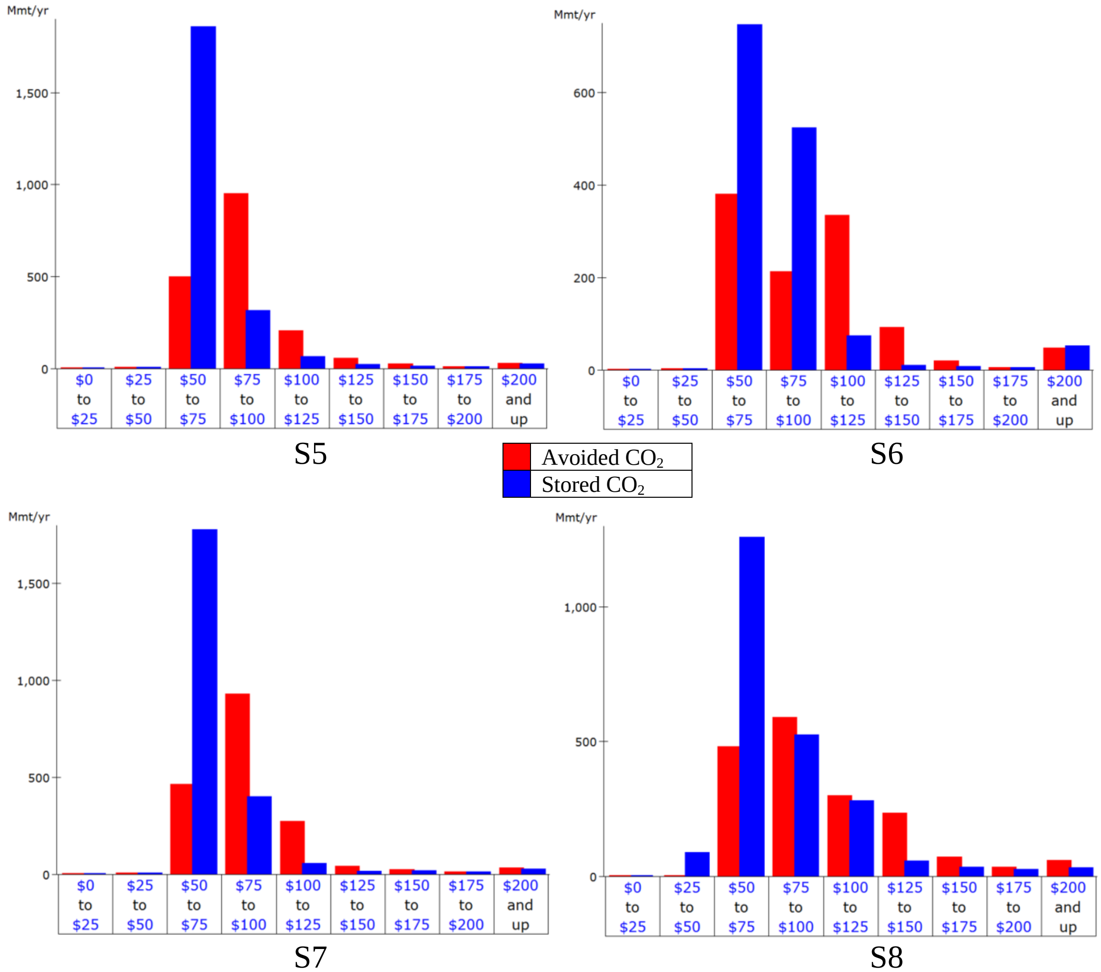

Figure 39. WECSsim scenario results for the storage and avoided CO_2 costs for 60-yr claim to storage space.

Note: Scenarios 5 through 8 illustrate the base case, option to limit source-to-sink distances to 50 miles or less, option to introduce competition between power plants for sink storage space for 60 years, and the option to not extract H_2O while also injecting CO_2.

Scenario 5 (S5) is similar to S1 with only the timeline changed from 30 to 60 years. The results for costs (avoided and storage) and storage space are virtually the same between S1 and S5 because of the very efficient use of pore space associated with brine extraction. Comparing S2 with S6 and S3 with S7 also show virtually identical results. This suggests the 50-mile limit has a stronger influence on the costs and storage capacities than the influence of plants now requiring a 60-yr timeline for the storage resource as well as limiting competition, respectively.

An important result is borne out of comparing S4 and S8. By securing 60 years' worth of rights to storage space while also including competition and unrestricted distance between the sources and sinks, a shortage of lower-cost storage appears. To put it another way, when competition becomes an issue for sink space, and the lifetime rights of the favorable sinks becomes an issue of scarcity, the cost to store CO_2 will rise unless water extraction allows for more space to store CO_2 within the favorable sinks.

Table 1. WECSsim national supply curve scenario results.
Note: Altering the distance-to-sink assumption, competition between power plants for sink space, extracting saline waters or not, and adjusting how long a power plant may have rights to sink space.

Scenarios[8]	Scenarios 1, 2, 3, & 4	Scenarios 5, 6, 7, & 8
Avoided Cost [Storage Cost] for 1 Gt/yr ($/tonne)	85.13 [61.53] [BC, S1] 143.32 [81.79] [S2] 87.12 [62.61] [S3] 79.20 [56.86] [S4]	85.20 [61.61] [S5] 143.32 [81.79] [S6] 87.16 [62.63] [S7] 95.57 [63.90] [S8]
Reduced [Stored] CO_2 @ $100 / tonne (Gt/yr)	1.4 [2.2] [BC] 0.6 [1.3] [S2] 1.4 [2.2] [S3] 1.5 [2.1] [S4]	1.4 [2.2] [S5] 0.6 [1.3] [S6] 1.4 [2.2] [S7] 1.1 [1.9] [S8]

Notes: Scenarios with 30-yr sink rights:
[BC, S1] Base Case, Scenario 1: No distance limit; competition for sinks; extract H_2O; 30-yr well lifetime & sink rights
[S2] Scenario 2: *50-mile limit*; competition for sinks; extract H_2O; 30yr well lifetime & sink rights
[S3] Scenario 3: No distance limit; *no competition for sinks*; extract H_2O; 30-yr well lifetime & sink rights
[S4] Scenario 4: No distance limit; competition for sinks; *do not extract H_2O*; 30-yr well lifetime & sink rights
Scenarios with 60-yr sink rights:
[S5] Scenario 5: No distance limit; competition for sinks; extract H_2O; 60-yr well lifetime & sink rights
[S6] Scenario 6: *50 mile limit*; competition for sinks; extract H_2O; 60-yr well lifetime & sink rights
[S7] Scenario 7: No distance limit; *no competition for sinks*; extract H_2O; 60-yr well lifetime & sink rights
[S8] Scenario 8: No distance limit; competition for sinks; *do not extract H_2O*; 60-yr well lifetime & sink rights

The take-away message from the scenarios presented in Table 1 is this: Two model constraints drive the majority of the modeling results. They include whether or not to restrict power plants from using saline formation sinks beyond 50 miles from the plant, and whether or not to extract water when the plants are competing with one another for sink space.

The scenarios presented in this analysis represent an estimate of potential costs to implement CCS across the fleet of coal- and gas-fired power plants in the U.S. before any substantial CCS effort is underway nationally. The no-competition supply curves (S3, S7) show little sensitivity to changes in storage resource or extraction of brine. This is because CCS, if considered using only one plant at a time, is not constrained by current estimates of geologic saline formation storage quality and quantity. The supply curves including sink competition thus represent a more realistic analysis of what costs might look like if large scale CCS were implemented in the U.S. With many large sources competing for geologic pore space, the sinks are more limited. Under the scenarios including competition for sinks, saline water extraction is a very important tool in managing the available CO_2 sinks. Thus, for large scale CCS, active reservoir management using brine extraction should be considered not only in areas with water scarcity issues at the surface to supplement power plant cooling requirements, but in all sinks as a hedge against overestimates of the overall size of the geologic resource to store CO_2.

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[8] Unless otherwise specified: well field lifetime = 30 years; financial lifetime assumption on plants and capital equipment = 20 years; both CO_2 is injected and H_2O is extracted from the saline formations; power plants must be within 50 miles of the potential saline formation sink to be considered; and water is to be returned to the power plant from the extraction. Competition for sink space is based on the ranked order of power plant to sink systems in order from least to most costly. See Roach et al. (2012), Kobos et al. (2011a,b), and Kobos et al. (2012) for additional information.

Putting the scenarios' costs results into perspective, S1 through S8 have an avoided cost range from 79–143 \$/tonne CO_2. The avoided cost ranges for the scenarios compare favorably with those presented in the literature. Versteeg and Rubin (2011), for example, explain that for coal-fired power plants using ammonia-based post-combustion CO_2 capture technology the costs are on the order of 63–133 \$/tonne CO_2.[9]

9.2 Single Plant to Single Sink CCS Scenario Discussions

Similar to the overarching fleet-level comparison analysis one can develop with WECSsim, a user-defined cost analysis will reveal the level of cost increases at a given power plant due to CCS. For example, assuming the San Juan Generating Station utilizes the Morrison Formation within the San Juan Basin, the levelized cost of electricity rises from approximately 6.7 cents/kWh before CCS to approximately 15 cents/kWh. Figure 40 illustrates the Power Costs tab and Summary page from WECSsim for this scenario.

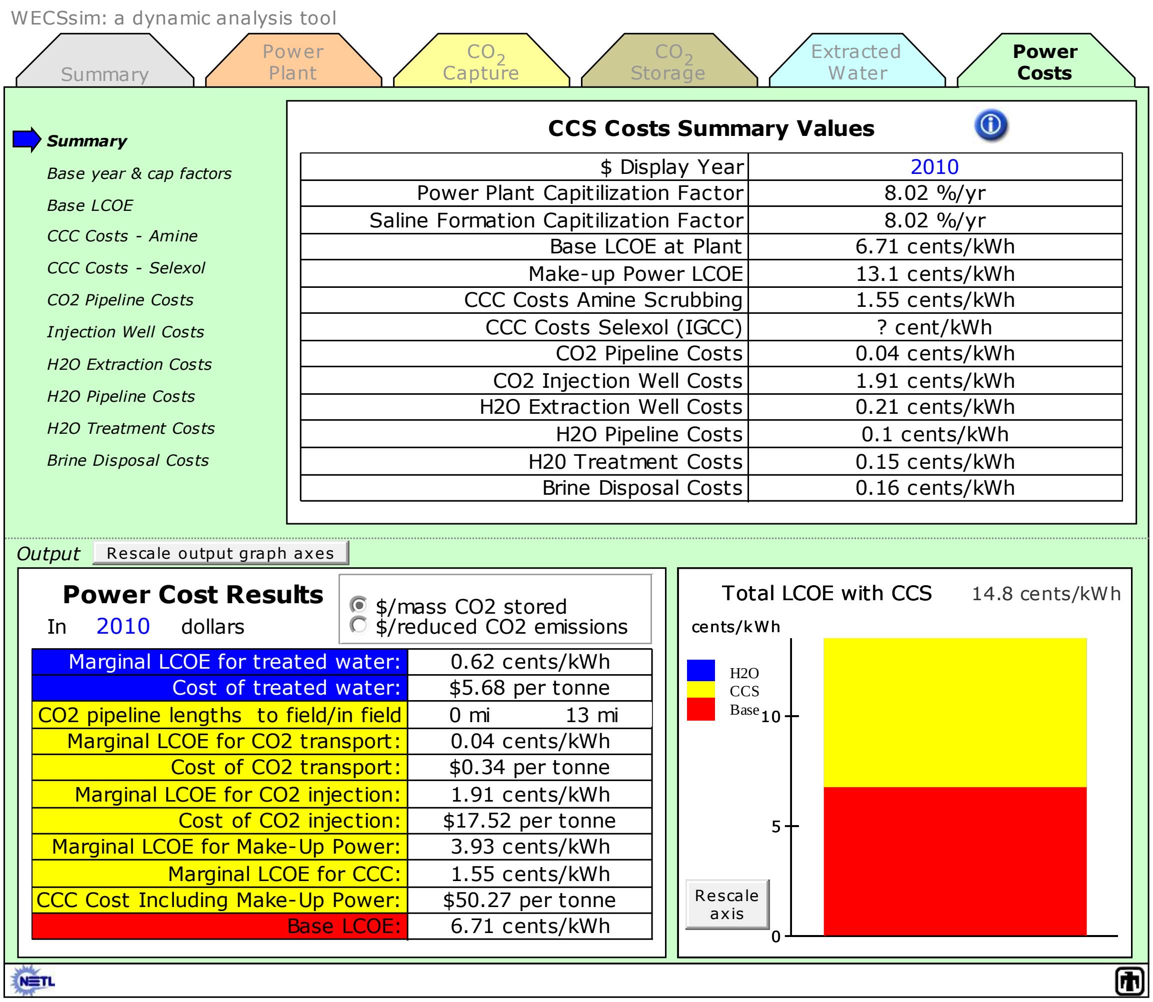

Figure 40. San Juan Generating Station Scenario using the Morrison Formation in the San Juan Basin.

[9] These costs were updated to 2010 \$US to compare with WECSsim values. Versteeg and Rubin reported \$US 2007 values of 60–127 \$/tonne CO_2. (OMB, 2009).

Using the modified NatCarb database, however, selects the Entrada Formation to store CO_2 from the San Juan Generating Station. This is primarily due to the overall lower cost of choosing the Entrada Formation (<13 ¢/kWh LCOE) over the Morrison (<15 ¢/kWh). Figure 41 illustrates the Power Costs tab information for this scenario.

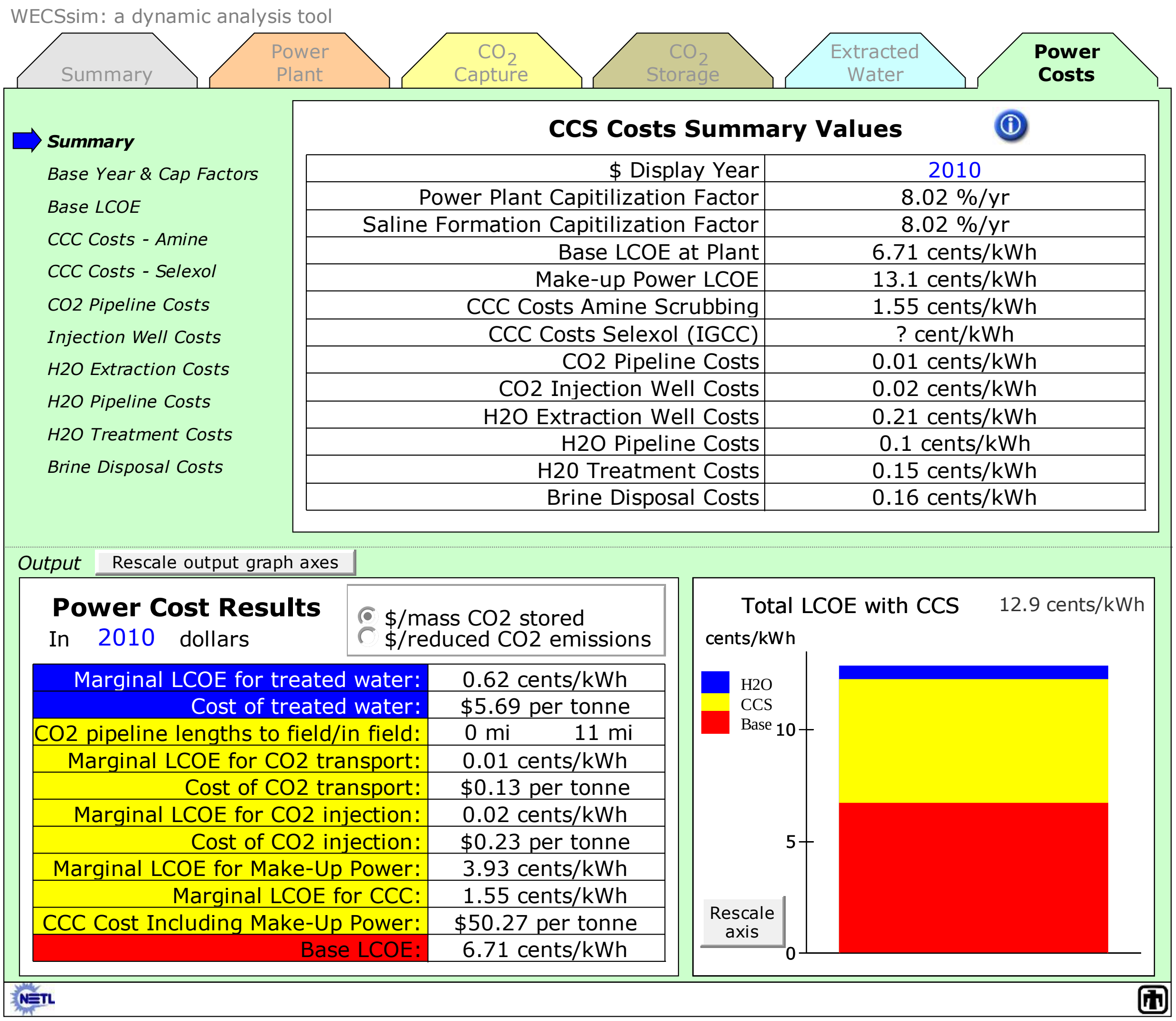

Figure 41. San Juan Generating Station Scenario using the Entrada Formation and other WECSsim default assumptions.

These power plant-specific scenarios illustrate one of many parameters the users of WECSsim could develop. Similar parameter changes could be developed and final system's costs assessed for CO_2 well and formation efficiencies, locations, water treatment costs, brine disposal options, and make-up power options to account for the parasitic energy required to drive the CCS systems, just to name a few.[10]

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[10] It is important to note that while in the many instances where the database includes both NatCarb and supplemental data from the rock type analysis described in Appendix E, similar efforts were not developed for the salinity levels of waters found in those formations beyond what was described in NatCarb. This was done to be conservative in the assumptions regarding potentially available saline water (volumes and salinities) for the

10. SUMMARY

The overarching purpose of the Water, Energy, and Carbon Sequestration Simulation Model (WECSsim) is to match the coal and natural gas power plants' CO_2 emissions in the U.S. to potential saline formation sinks to manage these emissions. Additionally, one of the purposes and unique capabilities of this analysis is having the ability to integrate water extraction from these formations to both address pressure buildup issues, along with alleviated potential additional water demands from the power plant(s) at the surface to capture CO_2. This water-oriented focus for large-scale CCS operations makes the WECSsim model unique in its combination of a CCS model with large water extraction and treatment modules all packaged within a user-friendly, software-based decision support tool.

Many factors will affect the ability to extract, treat, and utilize extracted waters from saline formations. These include the cost of the combined well fields to inject CO_2 and extract water, the type of technology used to treat the saline waters, and the distances involved to move the water back to the power plant or use for other purposes. Additionally, future work could incorporate rigorous Monte Carlo approaches with statistical distributions of the input parameters to refine the cost and volume of CO_2 and treated water estimates. Competition for sinks changes the costs very little if the working estimates of geologic resource size and quality are reasonable. However, if current estimates are overly optimistic, competition for sinks becomes very important, and brine extraction becomes economically compelling for large-scale CCS as a strategy to manage CO_2 emissions. Lastly, a set of break-even analyses could be developed while including new technologies such as CCS, water treatment, and site development techniques to understand up to what point a given set of technological combinations would result in a favorable cost profile for a single or national-scale CCS system with water extraction and treatment.

WECSsim analysis. Thus, if no information is available for a specific formation selected in the single-plant type of analysis, an error in the Power Cost tab will appear for the marginal LCOE of treated water and other related sections as a "?". In the fleet-level analysis, formations without saline waters available will be placed at the end of the supply curve such that they will appear so expensive (e.g., the Marginal LCOE for treated water will be "?" ¢/kWh and the Brine Disposal Costs will be populated with an illustrative, high number due to the model using a default of 9,999,999,999 holes drilled per extraction well). This gives the final result where neither the $/tonne stored nor avoided will be calculated, and will not be relevant to the fleet-wide supply curve.

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APPENDIX A: WATER, ENERGY, AND CARBON SEQUESTRATION SIMULATION MODEL (WECSSIM) EQUATIONS

The Water, Energy, and Carbon Sequestration Simulation Model (WECSsim) was developed using several modules. The power plant, CO_2 storage, geoassessment, water treatment, and economic modules all comprise key portions of the model's architecture. Table A-1 shows the key assumptions, data sources, and equations used in the model.

Table A-1. Power Plant Parameter Descriptions for WECSsim.

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Power plant location	decimal degrees	Power plant specific location. Latitude and longitude in decimal degrees	U.S. EPA eGRID (2007)
Nameplate capacity	Megawatts (MW)	Power plant specific nameplate capacity	U.S. EPA eGRID (2007)
Capacity factor	portion of time the unit is providing electricity	Power plant specific capacity factor	U.S. EPA eGRID (2007)
Elevation	meters (m)	Used to determine energy requirements for moving CO_2 and water from specific locations	U.S. EPA eGRID (2007)
Power plant base electricity generation	GWh/yr	Electricity generation value	GWh = 1000 * MWh nameplate capacity (GWh/yr) * capacity factor
Power plant base CO_2 generation	Mmt/yr	Annual CO_2 emissions from a power plant	Power plant base electricity generation (GWh/yr) * CO_2 emission rate (lb/MWh)
PC subcritical emission rate	lb/MWh	CO_2 emission rate - default	1,900 lb/MWh – Pulverized Coal, Subcritical - Rounded to the nearest 100 lb/MWh - Exhibit ES-2 on page 4 of NETL (2007b)
PC Supercritical emission rate	lb/MWh	CO_2 emission rate - default	1,800 lb/MWh – Pulverized Coal, Supercritical - Rounded to the nearest 100 lb/MWh - Exhibit ES-2 on page 4 of NETL (2007b)
IGCC emission rate	lb/MWh	CO_2 emission rate - default	1,700 lb/MWh – Integrated Gasification Combined Cycle - Exhibit ES-2 on page 4 of NETL (2007b)

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
NGCC emission rate	lb/MWh	CO_2 emission rate - default	800 lb/MWh – Natural Gas Combined Cycle - Rounded to the nearest 100 lb/MWh - Exhibit ES-2 on page 4 of NETL (2007b)
Gas Turbine emission rate	lb/MWh	CO_2 emission rate - default	1000 lb/MWh – Gas Turbine - Estimate based on NGCC value - Exhibit ES-2 on page 4 of NETL (2007b)
CO_2 emission rate	lb/MWh	Power plant specific CO_2 emissions - default	U.S. EPA eGRID (2007)
- Once through - Cooling tower - Cooling pond - Dry cooling - No cooling	N/A	Power plant specific cooling technology	Power plant specific data - U.S. EPA eGRID (2007) - User input override includes four parameters, including a no cooling option
Power plant water withdrawal rate	gal/MWh	Power plant & cooling technology specific water withdrawal rate - default	Power plant specific data - U.S. EPA eGRID (2007)
Power plant water consumption rate	gal/MWh	Power plant & cooling technology specific water consumption rate - default	Power plant specific data - U.S. EPA eGRID (2007)
PC subcritical water withdrawal rate	gal/MWh	Water withdrawal rate - default	For cases where power plant specifics are not known, e.g., user override. Assuming wet flue-gas desulfurization: **Once through: 27,113** **Cooling tower: 531** **Cooling pond: 17,927** **Dry cooling/no cooling: 76** - Values for once through, cooling tower, and cooling pond from Tables D-1 and D-4 of NETL (2010) - Dry cooling values taken as non-cooling demand shown in Figures 4-2 and B-1 of NETL (2009)

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
PC supercritical water withdrawal rate	gal/MWh	Water withdrawal rate - default	For cases where power plant specifics are not known, e.g., user override. Assuming wet flue-gas desulfurization: **Once through: 22,611** **Cooling tower: 669** **Cooling pond: 15,057** **Dry cooling/no cooling: 67** - Values for once through, cooling tower, and cooling pond from Tables D-1 and D-4 of NETL (2010) - Dry cooling values taken as non-cooling demand shown in Figure 4-2 and B-1 of NETL (2009)
IGCC water withdrawal rate	gal/MWh	Water withdrawal rate - default	For cases where power plant specifics are not known, e.g., user override. Assuming dry-fed slurry: **Once through: 11,002** (value interpolated between the values for PC supercritical and NGCC based on the cooling tower data) **Cooling tower: 226** **Cooling pond: 7,284** (value interpolated between the values for PC super critical and NGCC based on the cooling tower data) **Dry cooling/no cooling: 57** - Values for once through, cooling tower, and cooling pond from Tables D-1 and D-4 of NETL (2010) - Dry cooling values taken as non-cooling demand shown in Figure 4-2 and B-1 of NETL (2009)
NGCC water withdrawal rate	gal/MWh	Water withdrawal rate - default	For cases where power plant specifics are not known, e.g., user override. **Once through: 9,010** **Cooling tower: 150** **Cooling pond: 5,950** **Dry cooling/no cooling: 4** - Values for once through, cooling tower, cooling pond, and dry cooling from Tables D-1 and D-4 of NETL (2010)
Gas turbine water withdrawal rate	gal/MWh	Water withdrawal rate - default	For cases where power plant specifics are not known, e.g., user override. **Once through: 0** **Cooling tower: 0** **Cooling pond: 0** **Dry cooling/no cooling: 0**

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
PC subcritical water consumption rate	gal/MWh	Water consumption rate - default	For cases where power plant specifics are not known, e.g., user override. Assuming wet flue-gas desulfurization: **Once through: 138** **Cooling tower: 462** **Cooling pond: 804** **Dry cooling/no cooling: 68** - Values for once through, cooling tower, and cooling pond from Tables D-1 and D-4 of NETL (2010) - Dry cooling values taken as non-cooling demand shown in Figure 4-2 and B-1 of NETL (2009)
PC supercritical water consumption rate	gal/MWh	Water consumption rate - default	For cases where power plant specifics are not known, e.g., user override. Assuming wet flue-gas desulfurization: **Once through: 124** **Cooling tower: 518** **Cooling pond: 64** **Dry cooling/no cooling: 59** - Values for once through, cooling tower, and cooling pond from Tables D-1 and D-4 of NETL (2010) - Dry cooling values taken as non-cooling demand shown in Figure 4-2 and B-1 of NETL (2009)
IGCC water consumption rate	gal/MWh	Water consumption rate - default	For cases where power plant specifics are not known, e.g., user override. Assuming dry-fed slurry: **Once through: 32** (Value interpolated between the values for PC super critical and NGCC based on the cooling tower data) **Cooling tower: 173** **Cooling pond: 220** (Value interpolated between the values for PC super critical and NGCC based on the cooling tower data) **Dry cooling/no cooling: 53** - Values for once through, cooling tower, and cooling pond from Tables D-1 and D-4 of NETL (2010) - Dry cooling values taken as non-cooling demand shown in Figure 4-2 and B-1 of NETL (2009)
NGCC water consumption rate	gal/MWh	Water consumption rate - default	For cases where power plant specifics are not known, e.g., user override **Once through: 20** **Cooling tower: 130** **Cooling pond: 240** **Dry cooling/no cooling: 4** - Values for once through, cooling tower, cooling pond, and dry cooling from Tables D-1 and D-4 of NETL (2010)

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Gas turbine water consumption rate	gal/MWh	Water consumption rate - default	For cases where power plant specifics are not known, e.g., user override. **Once through: 0** **Cooling tower: 0** **Cooling pond: 0** **Dry cooling/no cooling: 0**
Power plant base water withdrawals	MGD	---	Power plant water withdrawal rate (defined above) * power plant base electricity generation (defined above)
Power plant base water consumption	MGD	---	Power plant water consumption rate (defined above) * power plant base electricity generation (defined above)
Fuel cost by plant type	¢/kWh	Default value for portion of LCOE calculation attributable to fuel costs	- Table on page 50 of NETL (2007b) **PC Subcritical: 2** **PC Supercritical: 1.9** **IGCC: 1.9** **NGCC: 5.3** **Gas Turbine: 5.3**
PC subcritical cooling cost	¢/kWh	Default value for the cost of the power plant cooling system	- Exhibits ES-2, 3-29, 3-62, 3-95, 4-12, 4-33, and 5-12 of NETL (2007b) - Figure 13 in Tawney et al. (2005) **Once through: 0.15** **Cooling tower: 0.24** **Cooling pond: 0.15** **Dry cooling: 0.64** **No cooling: 0**
PC Supercritical cooling cost	¢/kWh	Default value for the cost of the power plant cooling system	- Exhibits ES-2, 3-29, 3-62, 3-95, 4-12, 4-33, and 5-12 of NETL (2007b) - Figure 13 in Tawney et al. (2005) **Once through: 0.15** **Cooling tower: 0.23** **Cooling pond: 0.15** **Dry cooling: 0.62** **No cooling: 0**
IGCC cooling cost	¢/kWh	Default value for the cost of the power plant cooling system	- Exhibits ES-2, 3-29, 3-62, 3-95, 4-12, 4-33, and 5-12 of NETL (2007b) - Figure 13 in Tawney et al. (2005) **Once through: 0.14** **Cooling tower: 0.22** **Cooling pond: 0.14** **Dry cooling: 0.59** **No cooling: 0**

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
NGCC cooling cost	¢/kWh	Default value for the cost of the power plant cooling system	- Exhibits ES-2, 3-29, 3-62, 3-95, 4-12, 4-33, and 5-12 of NETL (2007b) - Figure 13 in Tawney et al. (2005) **Once through: 0.06** **Cooling tower: 0.10** **Cooling pond: 0.06** **Dry cooling: 0.27** **No cooling: 0**
Gas Turbine cooling cost	¢/kWh	Default value for the cost of the power plant cooling system	- Exhibits ES-2, 3-29, 3-62, 3-95, 4-12, 4-33, and 5-12 of NETL (2007b) - Figure 13 in Tawney et al. (2005) **Once through: 0** **Cooling tower: 0** **Cooling pond: 0** **Dry cooling: 0** **No cooling: 0**
PC Subcritical LCOE	¢/kWh	Default value for the levelized cost of energy (LCOE) by power plant and cooling type	- Exhibits ES-2, 3-29, 3-62, 3-95, 4-12, 4-33, and 5-12 of NETL (2007b) - Figure 13 in Tawney et al. (2005) **Once through: 6.30** **Cooling tower: 6.40** **Cooling pond: 6.30** **Dry cooling: 6.80** **No cooling: 6.30**
PC Supercritical LCOE	¢/kWh	Default value for the levelized cost of energy (LCOE) by power plant and cooling type	- Exhibits ES-2, 3-29, 3-62, 3-95, 4-12, 4-33, and 5-12 of NETL (2007b) - Figure 13 in Tawney et al. (2005) **Once through: 6.20** **Cooling tower: 6.30** **Cooling pond: 6.20** **Dry cooling: 6.70** **No cooling: 6.20**
IGCC LCOE	¢/kWh	Default value for the levelized cost of energy (LCOE) by power plant and cooling type	- Exhibits ES-2, 3-29, 3-62, 3-95, 4-12, 4-33, and 5-12 of NETL (2007b) - Figure 13 in Tawney et al. (2005) **Once through: 7.70** **Cooling tower: 7.80** **Cooling pond: 7.70** **Dry cooling: 8.20** **No cooling: 7.70**
NGCC LCOE	¢/kWh	Default value for the levelized cost of energy (LCOE) by power plant and cooling type	- Exhibits ES-2, 3-29, 3-62, 3-95, 4-12, 4-33, and 5-12 of NETL (2007b) - Figure 13 in Tawney et al. (2005) **Once through: 6.80** **Cooling tower: 6.80** **Cooling pond: 6.80** **Dry cooling: 7.00** **No cooling: 6.80**

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Gas Turbine LCOE	¢/kWh	Default value for the levelized cost of energy (LCOE) by power plant and cooling type	- Exhibits ES-2, 3-29, 3-62, 3-95, 4-12, 4-33, and 5-12 of NETL (2007b) - Figure 13 in Tawney et al. (2005) **Once through: 10.00** **Cooling tower: 10.00** **Cooling pond: 10.00** **Dry cooling: 10.00** **No cooling: 10.00**
GDP historic price index		Used to adjust LCOE, capital and O&M costs for CO_2 capture, power plants, desalination facilities, and well and pipeline construction to a reference year	Table 10.1 – Gross Domestic Product and Deflators Used in the Historical Tables: 1940–2014. Costs adjusted throughout the analysis: $US = 2010. OMB (2009)

Table A-2. Carbon Capture Parameter Descriptions for WECSsim.

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
PC subcritical - parasitic energy usage	%	Parasitic energy losses as a function of the percentage of CO_2 captured	NETL (2007a), Table ES-1: Summary of Technical and Economic Performance for Retrofitting a Pulverized Coal-Fired Plant. NETL (2002) Tables 4-6 and 5-6 **% CO_2 Captured: Parasitic Energy Losses** **0%: 0%** **30%: 10%** **50%: 16%** **70%: 23%** **90%: 30%** **100%: 40%**
PC supercritical - parasitic energy usage	%	Parasitic energy losses as a function of the percentage of CO_2 captured	NETL (2007a) Table ES-1 NETL (2002) Tables 4-6 and 5-6 **% CO_2 Captured: Parasitic Energy Losses** **0%: 0%** **30%: 10%** **50%: 16%** **70%: 23%** **90%: 30%** **100%: 40%**
IGCC - parasitic energy usage	%	Parasitic energy losses as a function of the percentage of CO_2 captured	NETL (2007a) Table ES-1 NETL (2002) Tables 4-6 and 5-6 **% CO_2 Captured: Parasitic Energy Losses** **0%: 0%** **30%: 6%** **50%: 11%** **70%: 15%** **90%: 20%** **100%: 27%**
NGCC - parasitic energy usage	%	Parasitic energy losses as a function of the percentage of CO_2 captured	NETL (2007a) Table ES-1 NETL (2002) Tables 4-6 and 5-6 **% CO_2 Captured: Parasitic Energy Losses** **0%: 0%** **30%: 7%** **50%: 12%** **70%: 17%** **90%: 22%** **100%: 29%**

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Gas Turbine - parasitic energy usage	%	Parasitic energy losses as a function of the percentage of CO_2 captured	NETL (2007a) Table ES-1 NETL (2002) Tables 4-6 and 5-6 **% CO_2 Captured: Parasitic Energy Losses** **0%: 0%** **30%: 8%** **50%: 14%** **70%: 19%** **90%: 25%** **100%: 34%**
Marginal LCOE for 90% CCS	¢/kWh	The cost effect of CCS for new power plants	Obtained by subtracting the LCOE with CCS from the LCOE without CCS. Values are from Exhibit ES-2 of NETL (2007b). **PC Subcritical: 5.5** **PC Supercritical: 5.2** **IGCC: 2.8** **NGCC: 5.0** **Gas Turbine: 2.90**
CO_2 production per HHV input	lb/MMBtu	CO_2 production rate per heat input	NETL (2007a) Table ES-1 **PC Subcritical: 203** **PC Supercritical: 203** **IGCC: 200** **NGCC: 140** **Gas Turbine: 119**
Marginal water withdrawal for 90% CO_2 capture	gal/MMBtu	---	NETL (2009) Figure B-2 in Appendix B **PC Subcritical: 24.7** **PC Supercritical: 24.4** **IGCC: 9.55** **NGCC: 22.1** **Gas Turbine: 22.1**

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Total CO_2 captured	Mmt/yr		Mass of CO_2 captured at original plant + make-up power plant CO_2 captured Where: Mass of CO_2 captured at original plant = power plant base CO_2 generation (defined above) * amount of CO_2 targeted for capture [%] Make-up power plant CO_2 captured = make-up power CO_2 generation * make-up power % CO_2 captured Where: Make-up power plant CO_2 generation = parasitic energy requirements * make-up power CO_2 generation rate Parasitic energy requirements = power plant base electricity generation (defined above) * parasitic energy requirements as a % of base generation Parasitic energy requirements as a % of base generation = Either user defined values for parasitic energy losses at 30, 50, 70 and 90% capture, OR parasitic energy use curves (defined above for PC-Sub, PC-Super, IGCC, Gas Turbine and NGCC) Make-up power % CO_2 captured = IF the make-up power plant CO_2 capture % is equal to the main power plant, THEN amount of CO_2 targeted for capture (defined above), ELSE make-up power % CO_2 captured (This forces the make-up power plant to be the same as the source power plant.)
Total CO_2 generation	Mmt/yr		Power plant base CO_2 generation (defined above) + make-up power plant CO_2 generation (defined above)
Emissions to the atmosphere with CCC	Mmt/yr		Total CO_2 generation (defined above) – total CO_2 captured (defined above)
Reduced emissions to the atmosphere with CCC	Mmt/yr		Power plant base CO_2 generation (defined above) – emissions to the atmosphere with CCC

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Levelized cost of make-up power	¢/kWh		(Default total LCOE by power plant & cooling type (defined above) + marginal LCOE for 90% CCS (defined above) * (make-up power % CO_2 captured (defined above) / 90%)) * (U.S. GDP Historic Price Index Base / U.S. GDP Historic Price Index base for default make-up power LCOE values) Where: U.S. GDP Historic Price Index base for default make-up power LCOE values = 2007 Values from NETL (2007b) Costs adjusted throughout the analysis: $US = 2010.
Additional water withdrawals due to CCC	MGD		Make-up power water withdrawals + marginal absolute water withdrawal due to CCS Where: Make-up power water withdrawals = parasitic energy requirements (defined above) * makeup power water withdrawal rate Makeup power water withdrawal rate = choice between 530 [gal * MWh^{-1}] (default value for supercritical pulverized coal with cooling tower) OR marginal water withdrawal per mass of CO_2 captured at 90% capture Marginal absolute water withdrawals due to CCS = marginal water withdrawal rate due to CCS * total CO_2 captured (defined above) Marginal water withdrawal rate due to CCS = choice between user specified value with default of 300 [gal * $tonne^{-1}$] (based on default value for subcritical pulverized coal plant with 90% captured CO_2) OR marginal water withdrawal per mass of CO_2 captured at 90% Where: Marginal water withdrawal per mass of CO_2 captured at 90% = Marginal water withdrawal for 90% CO_2 capture (defined above) / (0.9 * CO_2 production per HHV input (defined above))
Total power plant water withdrawal with CCS	MGD		Marginal absolute water withdrawal due to CCS (defined above) + power plant base water withdrawals (defined above)
Change to total water withdrawals due to CCC	%		Additional water withdrawals due to CCC / power plant base water withdrawals (defined above)

Table A-3. CO_2 Storage Parameter Descriptions for WECSsim

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Distance source to formations	km	Great circle distance from the power plant to formation centroids	For more detail on the formation shape simplification to allow for distance calculation, see Appendix C IF power plant is above formation, then distance is 0, ELSE great circle distance from power plant to formation centroid Where: Great circle distance from power plant to formation = Earth Radius [6371 km] * Arccosine(Sine(power plant location) * Sine(formation centroid) + Cosine(power plant location) * Cosine(formation centroid) * Cosine(power plant location – formation centroid))
Formation elevation	m	The average ground surface elevation of the projected formation boundary	Choice between user input, and average elevation of either onshore formation (from a digital elevation map) or offshore formation Offshore and partially offshore formation subsurface elevation was determined from geospatial analysis using offshore bathymetry data for 14 polygons.
Formation total area	km^2	Area of formations used in analysis	Choice between user input, OR simplified formation shape (See Appendix C) OR calculated from NatCarb geospatial data (NETL, 2008)
Formation sequestration depth utilized	m	Depth of the formation where CO_2 injection and water extraction occur	(Depth to the top of formation + formation thickness) / 2 Where: A choice between formation thickness, which includes: Reported formation thickness (NatCarb, 2008) Formation thickness from SNL well analysis Formation thickness from potentially intersecting wells User specified input Multiple reports describe the processes used to determine the depths and thicknesses utilized in WECSsim. See Kobos et al. (2010b) and Kobos et al. (2011c) for more detail
Geothermal gradient by formation	C/km	Used to help determine CO_2 density at depth	Geospatial analysis of the geothermal gradient employed data from Southern Methodist University (SMU, 2012) Geothermal well data for onshore formations were analyzed for formations utilized in WECSsim. This was done to determine the average geothermal gradient for each onshore formation. For offshore formations, the NOAA NODC Ocean Climate Laboratory – World Ocean Atlas (NOAA, 2009) temperature data were employed to determine the ocean temperature at the ocean floor depth above the outline of the saline formation. This information then helps determine the geothermal gradient for the offshore and partially offshore portion of some formations.

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
CO_2 density for storage estimates	kg/m^3		Choice between calculated CO_2 density or user defined Where: Calculated CO_2 density = for each pressure, the model uses a lookup table to find the density associated with the formation temperature Lookup table is built using the relationship between Pressure, Temperature and Density calculated in TOUGH2. Took values from a file called CO2TAB [T2Well/ECO2N code], which included densities (and viscosities) of CO_2 at each of 127 pressures from 1 to 600 bar and each of 51 temperatures from 3.04 to 103.04 degrees C. Nineteen pressures (1, 25, 37.7691, 48.5364, 61.5337, 73.9045, 88, 100, 140, 180, 220, 260, 300, 340, 380, 420, 460, 476, 600) and 12 temperatures (3.04, 13.04, 23.04, 31.04, 33.04, 43.04, 53.04, 63.04, 73.04, 83.04, 93.04, 103.04) were kept along with the density values associated with all possible combinations of these 19 pressures and 12 temperatures. See Pruess (2005) for more detail. Constants used to calculate density include the following: Geothermal gradient by formation (defined above), which includes: - Surface temperature by formation - Deep ocean temperature over offshore formation - Percentage of formation offshore Formation depth utilized (defined above) Background pressure at sequestration depth, which includes: - Depth of ocean above sediments - Density of sea water [1.025 $g*cm^{-3}$] - Acceleration of gravity [9.8 $m*s^{-2}$] Formation pressure after injection, which includes: - fracture pressure (defined below) * fracture safety factor (defined below)
Mass of CO_2 to be sequestered	Mmt/yr	Choice between only sequestering CO_2 at the original power plant, or also sequestering make-up power plant CO_2	Total CO_2 captured (defined above) OR mass of CO_2 captured at original plant (defined above)

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Pore space required for CO_2 sequestration	km^3/yr	How much pore space is required for each formation, annually, to store CO_2	Mass of CO_2 to be sequestered (defined above) / CO_2 density for storage estimates (defined above)
Formation porosity		Used to determine the area available for CO_2 injection	A choice between different porosities, including: - NETL (2008) reported porosity - Rock type based mean porosity - User specified input See Appendix E for the rock type based mean porosity
Estimated formation life as power plant sink	yr	The approximate remaining lifetime of the sink, neglecting losses or other outflows	Formation capacity / mass of CO_2 to be sequestered (defined above) Where: Formation capacity is a choice between different storage estimates, including: - NETL (2008) reported storage estimate - Formation calculated CO_2 storage resource (defined below) - User input
Total formation area required for sequestration	km^2		(Average lifetime of an injection well * mass of CO_2 to be sequestered (defined above)) / storage resource per formation area Where: Average lifetime of an injection well = 30[yr] Johnson and Ogden (2011); Szulczewski et al. (2012) Storage resource per formation area = formation pore space per area * CO_2 sequestration density for storage estimates (defined above) * formation sequestration efficiency Formation pore space per area = formation thickness (defined above) * formation porosity (defined above) Formation sequestration efficiency = choice between: - User input - Default storage efficiency calculated as a function of geologic properties and well location. See Appendix F for more detail.
Formation calculated CO_2 storage resource	Mmt		Storage resource per formation area (defined above) * formation area available for CO_2 storage [same as formation total area (defined above)]
Formation permeability	mD		For a complete discussion on determining formation permeability and its use in the modeling framework, see Appendix F.3

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Effective sequestration depth	m	Depth where CO_2 sequestration will occur	Formation sequestration depth utilized (defined above) + ocean depth above sediments The ocean depths are needed to determine the correct depth for offshore and partially offshore formations
Bottom hole fracture pressure	Pa	Determines fracture pressure at a certain depth	Choice of user input or, Effective sequestration depth (defined above) * fracture gradient Where the fracture gradient constant is defined as 0.68 $psi*ft^{-1}$. See discussion in Appendix F.3 for more detail.
Maximum pressure range for CO_2 injection in formation	Pa		(Bottom hole fracture pressure * fracture safety factor) – background pressure at sequestration depth (defined above) Where the fracture safety factor default is 90% For a more complete discussion on how formation pressure is determined and used in the modeling framework, see Appendix F.1 and F.3
Injection and extraction well spacing	km	The distance between injection wells and extraction wells	Used for CO_2 injection and water extraction scenarios For a more complete discussion on how injection and extraction well spacing is calculated, see Appendix F.
Injection well spacing	km	Distance between injection wells	Used for CO_2 injection only scenarios where water is not extracted For a more complete discussion on how injection and extraction well spacing is calculated, see Appendix F.
Injectivity for extraction and injection	m^3/da/atm	The rate at which CO_2 can be injected into a subsurface formation	Used for CO_2 injection and water extraction scenarios For a more complete discussion on how injection and extraction well spacing is calculated, see Appendix F.
Injectivity for injection only	m^3/da/atm	The rate at which CO_2 can be injected into a subsurface formation	Used for CO_2 injection-only scenarios where water is not extracted. For a more complete discussion on how injection and extraction well spacing is calculated, see Appendix F.
Volumetric injection rates	MGD	The volumetric flow rate through the injection well	For a more complete discussion on how the volumetric injection rate is calculated, see Appendix F.3.
Mass injection rates	tonnes/da	The mass injection rate through the injection well	Volumetric injection rate * CO_2 density at injection wellhead For a more complete discussion on how the mass injection rate is calculated, see Appendix F.3.

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Number of required injection wells		The required number of injection wells needed to inject a certain amount of CO_2	Choice of user input or calculation The number of injection wells varies on injection only, or injection and water extraction scenarios. For a more complete discussion on how this is calculated, see Appendix F.3.
Expected boreholes drilled per completed injection well		This is the total number of boreholes drilled as those that intersect low TDS water will not be completed as injection wells	Utilizes a straight default percentage for all wells, or a changing percentage from a user defined 'well field experience curve' where the odds of drilling a useable well increase with the number of wells drilled. For example, Useable Well # Odds x 1-(1-ios)*(1-imp)^(x-1) where ios is initial odds of success, and imp is the improvement in odds 1 1-0.4 = 0.6 2 1-0.4*(1-0.1) = 1-0.36 = 0.64 3 1-0.4*(1-0.1)^2 = 1-0.324 = 0.676 4 1-0.4*(1-0.1)^3 = 1-0.2916 = 0.7084 5 1-0.4*(1-0.1)^4 = 1-0.26244 = 0.73756 etc.
Total well field CO_2 pipeline length	km	Distance of piping necessary for moving CO_2 to injection locations. See Appendix F.4 for additional information.	Injection field trunk pipeline distance + well field branch lengths Where: injection field trunk pipeline distance = injection well design spacing * injection field trunk segments injection field trunk segments = an integer number found from a lookup table that gives trunk segments required for a given number of wells assuming a square well field with a trunk line running through the middle with symmetrical branch lines extending perpendicularly on each side of the trunk line well field branch lengths = injection well design spacing * (injection wells utilized -1) Where: injection well design spacing is determined based on formation properties and desired lifetime of the well field For more information see Appendix F.4.

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Competition for CO_2 sinks	logical	A switch that allows the model user to simulate competition for sinks	This only applies to entire power plant fleet runs. By default, this is turned off, even for fleet level analysis When turned on: Once a power plant selects the most cost effective formation to use, the portion of that formation needed by that power plant is removed from consideration by other power plants. As the model runs with this switch enabled, the overall sink resource grows smaller. Therefore, CO_2 storage costs may rise for some power plants
Formation boundary condition	logical	A switch that changes the assumed boundary condition of the sinks	By default all formations are assumed to have closed boundaries (no flow, and no pressure dissipation across the boundaries). The user can force the boundaries to be open (constant pressure condition) boundaries with this switch.

Table A-4. Water Extraction and Treatment Parameter Descriptions for WECSsim.

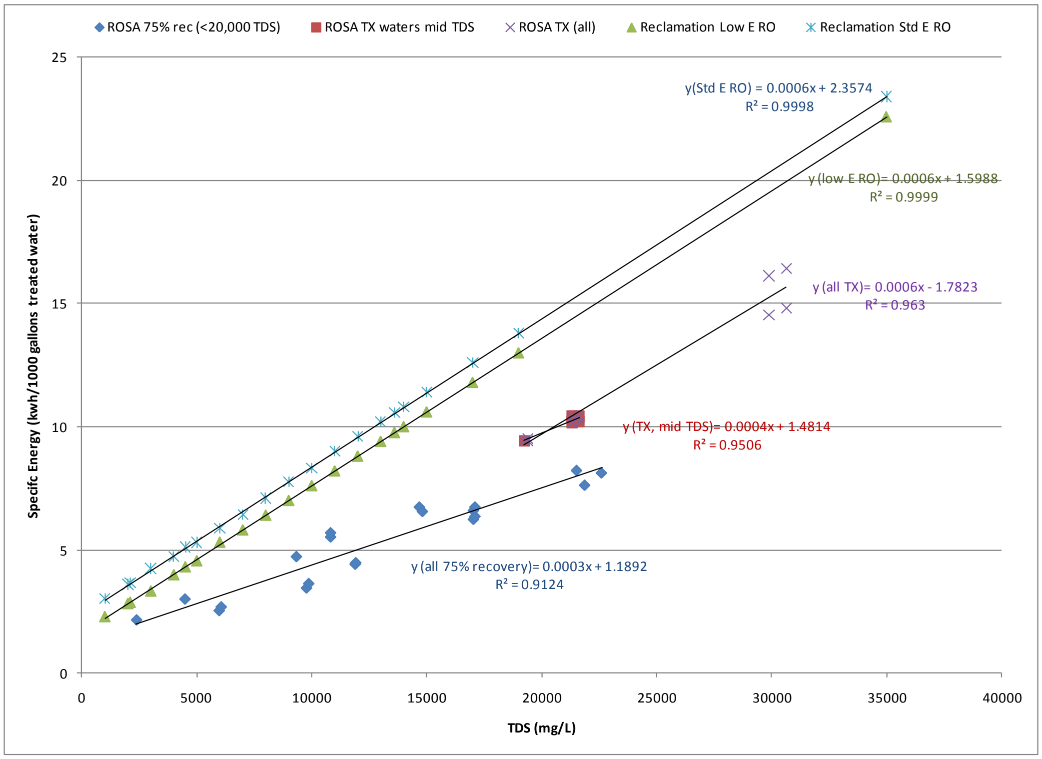
Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Potentially intersecting wells for each depth interval	# of wells in salinity range	Intersection of Kansas Geologic Survey wells with NatCarb saline formations	Spatial intersection of 2006 Kansas Geologic Survey (KGS, 2006) with NatCarb saline formation polygon data (NETL, 2008) for wells that have depths reported between 2,500 and 5,000 feet, 5,000 and 7,500 feet, and 7,500 feet to 10,000 feet. Distributions of salinity range from 0 to 10 ppt, then every 2 ppt, with the final category of 40 ppt and above.
Average salinity of potentially intersecting wells for each depth interval	ppt	The average salinity of water in each formation at each extraction depth interval	Calculated from potentially intersecting wells above, by taking the weighted average of all wells between 2,500 and 10,000 feet. Results are average salinities between 2,500 and 5,000 feet, 5,000 and 7,500 feet, and 7,500 feet to 10,000 feet, which are the three extraction intervals.
Percentage of available extraction wells by depth	%	The percentage of wells within the appropriate salinity range, considering formation depths and thicknesses	This is calculated by dividing the wells with the appropriate salinity range by the total number of wells, for each depth interval (2,500 and 5,000 feet, 5,000 and 7,500 feet, and 7,500 feet to 10,000 feet), considering formation specific thicknesses and depth to top of formation within the range of 2,500 feet to 10,000 feet.
Expected number of boreholes drilled per completed extraction well		Expected number of boreholes drilled per completed extraction well for each brine disposal method	This is calculated as 1 / the percentage of available extraction wells by depth (probability in %) to get the number of boreholes per completed extraction well
Extraction well cost for depth and pumping rate	$/ft/MGD	Cost to install a well that can handle a specific flow rate	Calculated from data in the USBR Desalting Handbook for Planners (2003). This is done by taking three well depths (400, 600 and 800 feet) and conducting a curve fit in order to extrapolate to depths used in this analysis. The initial value is in year 2000 $US and only assumes capital equipment costs to then update them to 2010 $US.
Extraction well average depth by formation	ft	The result of the model choosing the extraction depth based on the lowest cost for desalination	The result here is also a function of the parameters that look at the number of boreholes drilled per successful well due to the probability of intersecting a formation with the desired salinity. This is the result of the product of the expected number of boreholes drilled per completed extraction well, the extraction well cost for depth and pumping rate, and the average depth of the three extraction well intervals (3,750 feet, 6,250 feet and 8,750 feet).

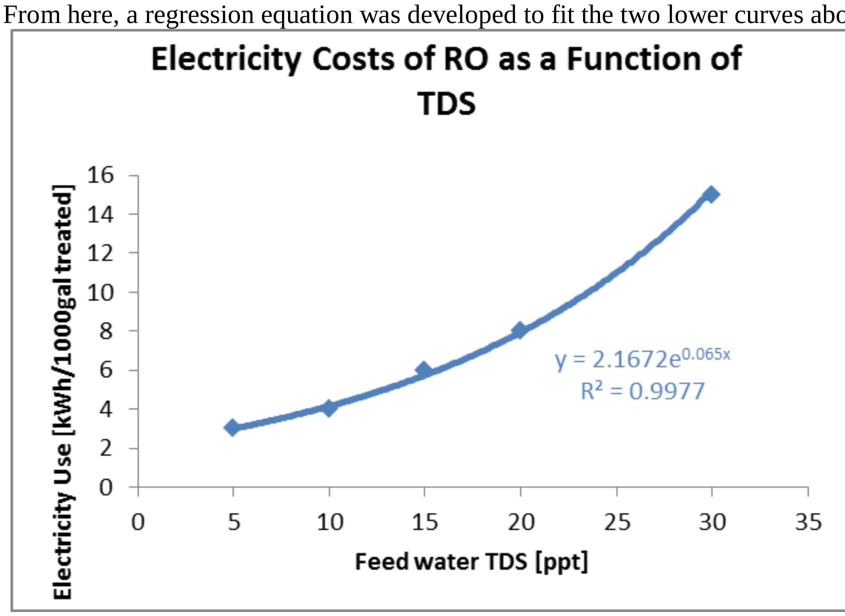
Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Salinity average by formation	ppt	The salinity taken from the average salinity of potentially intersecting wells for each depth interval for the chosen extraction depth	The salinity for each formation at the average depth interval, which is taken from the average salinity of potentially intersecting wells for each depth interval
Efficiency factor for extraction volume	%	Expected efficiency as a function of saline formation and depth interval for determining how much water to extract	Takes the smallest value of either the maximum RO efficiency (see definition in RO parameters below) or the sum of the RO plant efficiency intercept and slope (see definition in RO parameters below) multiplied by the salinity from chosen depth interval
Extracted water volume by formation	MGD	Used if modeling equal volumes of water extracted and CO_2 injected	Calculated as a product of the pore space by formation, required for CO_2 storage and the extraction as a percentage of volumetric CO_2 injection
Extracted water volume by formation - brine injection dependent	MGD	The estimate of how much water is extracted as a function of whether brine is reinjected or not	If brine is to be reinjected, it is the product of the extracted water volume by formation and 1 / the efficiency factor for the extraction volume. If there is no brine reinjection, it is the extracted water volume by formation calculated above.
Extraction wells required by formation		The number of extraction wells required as a function of the amount of CO_2 injected	Calculated from the number of CO_2 injection wells utilized
Extracted water volume per well	MGD	The amount of water extracted per completed extraction well	Extracted water volume by formation – brine injection dependent (defined above) / Extraction wells required by formation (defined above)
Water density	lb/ft^3	Density of water at standard temperature and pressure	Used to determine energy requirements for pumping water 62.4273
Brine density to concentra-tion slope	%/ppt	Used to determine the brine density based on incoming concentration	Cabot Specialty Fluids (CSF, 2011) Section A2, Table on page 5 Density of 1.2 $g*ml^{-1}$ for a 30% brine (of sodium and potassium). Approximated slope of 20% additional density for 300 ppt TDS

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Acceleration of gravity	m/s^2	Used for potential energy calculations	9.8
Approximate brine concentra-tion	ppt	Brine concentration as a function of RO plant efficiency	Assumes the RO process will remove 100% of salts, and those end up in brine Salinity average by formation / (1 – RO plant efficiency)
Brine density	kg/liter	Density of extracted brine	Water density * (1 + approximate brine concentrations * brine density to concentration slope)
Water pipeline friction loss		Used to determine energy required to transport water	Target head loss per length traveled in model. See Kobos (2010a) Appendix B. The model assumes a pipeline design to allow for a friction loss of 3 feet per 1000 feet of pipeline distance. 0.003
Elevation change from power plant to disposal point	m	Change in elevation between power plant and disposal point	Used to determine the energy required for brine disposal Elevation of disposal location – power plant elevation (all defined above)
Elevation change from formation to power plant	m	Change in elevation between formation and power plant	Used to determine the energy required for moving extracted water and injected brine
Potential energy to extract water	kWh/yr	How much energy it takes to extract saline water	Extracted water volume by formation * water density * acceleration of gravity * extraction well average depth by formation (all defined above)
Potential energy to move extracted water	kWh/yr	How much energy it takes to move extracted water	Extracted water volume by formation * water density * acceleration of gravity * distance source to formations * water pipeline friction loss * elevation change from formation to power plant (all defined above)
Potential energy to move brine for injection	kWh/yr	How much energy it takes to inject brine	Brine concentrate * brine density * acceleration of gravity * (distance to source formations utilized * water pipeline friction loss – elevation change from formation to power plant) (all defined above)
Potential energy to move brine for disposal	kWh/yr	How much energy it takes to move brine for off-site disposal	Brine concentrate * brine density * acceleration of gravity * (distance from treatment to disposal method utilized * water pipeline friction loss + elevation change from power plant to disposal point) (all defined above)
Water Treatment Assumptions, Equations, and Sources			
Extracted water volume per well	MGD	The amount of water extracted per completed extraction well	The extracted water volume by formation - brine injection dependent (defined above) / extraction wells required by formation (defined above)

<table>
<tr><th>Parameter</th><th>Unit(s)</th><th>Description</th><th>Equation, Assumption, and/or Source</th></tr>
<tr><td>Electricity use per treated water output – RO ROSA results</td><td colspan="3">Reverse Osmosis System Analysis (ROSA) by DOW was used to develop a relationship between TDS and power consumption of the RO process for several waters (Cappelle, 2010).

This figure shows the modeled results for specific energy (kWh/1000 gallons of permeate produced).



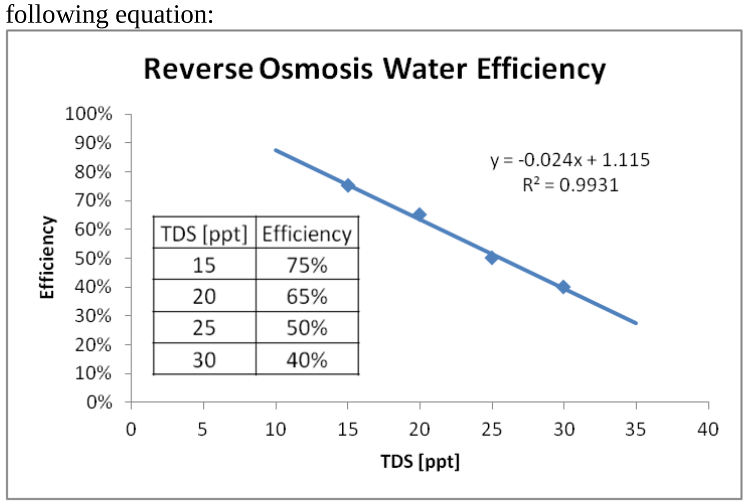
From here, a regression equation was developed to fit the two lower curves above:


Energy[kWh/1000gallons permeate] = 2.1672exp(0.065*TDS[ppt])</td></tr>
</table>

<table>
<tr><th>Parameter</th><th>Unit(s)</th><th>Description</th><th>Equation, Assumption, and/or Source</th></tr>
<tr><td>Electricity use per treated water output – RO USBR method</td><td>kWh/1000 gallons</td><td>The amount of electricity used to lower the TDS of water treated using RO</td><td>Calculated from the USBR Desalting Handbook for Planners (2003). USBR Figure 7-8 describes the energy intensity for several types of desalination: electrodialysis-reversal, low energy reverse osmosis, and standard reverse osmosis. The analysis assumes that standard reverse osmosis membranes will be utilized in the High Efficiency Reverse Osmosis (HERO) systems to provide a conservative estimate

Linear equation derived is: kWh/1000 gal treated = 0.0006*TDS + 2.411</td></tr>
<tr><td>RO plant efficiency - ROSA</td><td>%</td><td>Percentage that will be applied to determine what percent of extracted water will be available for use after treatment</td><td>From Cappelle (2010):
• 75% recovery for waters up to 20 ppt
• 65–70% recovery for waters near 20 ppt
• 40–50% recovery for waters between 25 and 30 ppt

Using the following relationship, the following four points are defined and plotted:
TDS[ppt] Efficiency
15 75%
20 65%
25 50%
30 40%

The best fit linear line through those points is defined by the following equation:


Efficiency = 1.115 - 0.024*TDS[ppt]</td></tr>
<tr><td>RO treated water stream</td><td>MGD</td><td>The volume of water available for use after RO treatment</td><td>Extracted water volume * RO plant efficiency (both defined above)</td></tr>
<tr><td>Brine concentrate stream</td><td>MGD</td><td>The volume of brine resulting from RO treatment</td><td>Extracted water volume - RO treated water stream (both defined above)</td></tr>
</table>

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Electricity use for RO	kWh/yr		Electricity use per treated water output * RO treated water stream (both defined above) (As a function of either the ROSA or USBR method)
RO treatment plant capacity factor	%	Required to accommodate the average flow due to treatment plant downtime	85% default from Cappelle (2010)
RO treatment plant capacity	MGD	Reduced treatment volume due to capacity factor	RO treated water stream / RO treatment plant capacity factor
RO treatment plant inflow	MGD	The inflow to the treatment plant when operating at capacity	RO treatment plant capacity / RO plant efficiency (both defined above) (As a function of either the ROSA or user input method)
Additional water demand served by extracted water	%		RO treated water stream / Additional water withdrawals due to CCC
Brine Disposal Assumptions, Equations, and Sources			
Distance from treatment to brine injection	km	Distance to move brine for reinjection if chosen as a disposal option	distance to source formations utilized or user defined
default distance from power plant to brine disposal location	km	Great circle distance to the ocean	The great circle distance to the ocean. Calculated or user defined Earth Radius * Arccosine(Sine(power plant location) * Sine(Ocean disposal centroids) + Cosine(power plant location * Cosine(Ocean disposal centroids) * (Cosine(power plant location – ocean disposal centroids)) / 1 radian
Net evaporation at each power plant location	in/yr	Evaporation estimate for each power plant	User defined, or ½ degree resolution net evaporation raster created in GIS referenced to power plant locations. Net evaporation is defined as average annual potential evaporation less average annual precipitation.
Required area of evaporation ponds	acre	The required surface area of evaporation pond if chosen as a disposal option	User defined, or When net evaporation is > 0, Brine concentrate / net evaporation at each power plant (both defined above)

Table A-5. Integrating Cost Module Parameter Descriptions for WECSsim.

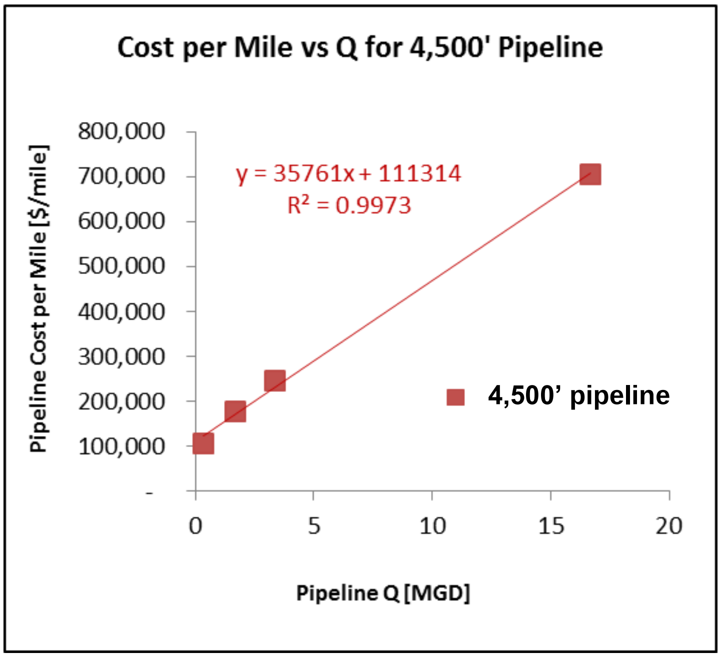
Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Saline formation capitalization factor	%/yr	Determines the capitalization factor for the saline formation with a time period based on the smaller of loan period or power plant remaining years online	User defined (assumed 17.5% default that may be adjusted), or the calculated periodic payment (PMT) function returns the periodic payment on an investment based on periodic, constant payments and a constant interest rate For each particular saline formation, this function returns the periodic payment when the payment is constant (e.g., an annuity payment): Present Value (PV) * (1+r)^ n_c + PMT/r*[(1+r)^n_c-1]+Future Value (FV) = 0 Where: r = the interest rate per period (Assumed default is 5%/yr) n_c = the number of periods where: c = years' worth of usable storage capacity per Saline Formation or the years remaining for the power plant to remain online; whichever is less
Power plant capitalization factor	%/yr	Calculate capitalization factor for the power plant with a time period based on the smaller of loan period or power plant remaining years online	User defined (assumed 17.5% default that may be adjusted), or the calculated periodic payment (PMT) function returns the periodic payment on an investment based on periodic, constant payments and a constant interest rate For each particular Saline Formation, this function returns the periodic payment when the payment is constant (e.g., an annuity payment): Present Value (PV) * (1+r)^ n_c + PMT/r*[(1+r)^n_c-1]+Future Value (FV) = 0 Where: r = the interest rate per period (assumed default is 5%/yr) n_c = the number of periods (years remaining for the power plant online; base case of 20 years beyond 2010, or, user defined to simulate an extended lifetime for the selected power plant under the single plant to single CO_2 sink site user option within WECSsim)
Annualized costs without makeup power	USD/yr	Cost of CO_2 Capture and Compression (CCC) using either an Amine-based system (three options) or Selexol-based capture technology	CCC Amine capital cost * Power Plant capitalization factor utilized + CCC amine fixed O&M cost + CCC amine variable O&M cost Where: CCC amine capital cost [$1000] = ($112.8 * CO_2 captured + 119,453) CCC amine fixed O&M cost [$1000] = (0.4 [$/tonne] * CO_2 captured + 11,556.9) CCC amine variable O&M cost = (6.2 [$/tonne] * CO_2 captured + 1,838.6)

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
			Or Selexol capital costs * Power plant capitalization factor utilized + Selexol annual costs Where: Selexol capital costs = Selexol capital cost $retrofit_{st}$ * CO_2 captured Selexol annual costs = (Selexol CCC fixed O&M + Selexol CCC variable O&M + IGCC marginal fuel use with CCC * Unit cost of coal * CO_2 captured Where: Selexol CCC fixed O&M = \$0.35 * $tonne^{-1}$ (Average of the GEE, CoP and Shell technologies; With and without CO_2 capture and compression, take the average per technology, divided by the CO_2 emissions with and without capture. Then take the average of those three results; NETL, 2007b) GEE: (\$24,306,610*yr^{-1} (w/capture) - \$22,589,291*yr^{-1} (w/o capture)) / (1,123,781 lb*hr^{-1} (w/o capture) - 114,476 lb*hr^{-1} (w/capture)) CoP: (\$23,980,481*yr^{-1} (w/capture) - \$21,951,999*yr^{-1}) (w/o capture)) / (1,078,144 lb*hr^{-1} (emissions w/o capture) - 131,328 lb*hr^{-1} (emissions w/capture)) Shell: (\$22,621,970*yr^{-1} (w/capture) - \$2,2371,481*yr^{-1} (w/o capture)) / (1,054,221 lb/hr (emissions w/o capture) - 103,041 lb*hr^{-1} (emission w/capture)) Selexol CCC variable O&M = \$0.57*$tonne^{-1}$ (Average of the GEE, CoP and Shell technologies; NETL, 2007b) GEE: (\$31,501,967*yr^{-1} - \$29,136,149*yr^{-1}) / (1,123,781 lb*hr^{-1} - 114,476 lb*hr^{-1}) CoP: (\$30,936,762*yr^{-1} - \$27,699,648*yr^{-1}) / (1,078,144 lb*hr^{-1} - 131,328 lb*hr^{-1})

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
			Shell: ($29,113,271*yr^{-1} - $28,182,450*yr^{-1}) / (1,054,221 lb*hr^{-1} - 103,041 lb*hr^{-1}) IGCC marginal fuel use with CCC = $0.068*tons^{-1}*yr^{-1} (lb*hr^{-1}) (Average of the GE, CoP and Shell technologies; NETL, 2007b). Unit cost of coal = $42.11*ton^{-1} (NETL, 2007b) CO_2 Captured = power plant CO_2 generation * CC carbon capture % Amount O&M = Operations and Maintenance st = Selexol Technology[General Electric Energy (GEE) ($166 hr *lb^{-1}), ConocoPhillips (CoP), and Shell gasifiers ($129 hr *lb^{-1}), (NETL, 2007b); default set to ConocoPhillips' value of $190 hr *lb^{-1} to be conservative such that greenfield sites may be expensive to develop (e.g., retrofit)]
Base / Base Year for $ Values [specific to the technology component, e.g., Amine CO_2 Capture Costs]	USD	Applying inflation factors where necessary to standardize costs throughout the reporting	The overall systems costs are updated throughout the analysis to 2010 U.S. dollars ($US) as an initial default that can be adjusted by the model user to different years where desired. The inflation correction factor is a function of the base year the cost data were reported in (M_{Year}) divided by the inflation factor for the base year reported for this study (N_{Year}) $I = M_{Year} / N_{Year}$
Levelized CO_2 Capture and Compression (CCC) Costs of electricity (LCOE) without make up power	¢/kWh	---	Annualized costs without make-up power / power plant base electricity production$_i$ (both defined above) Where: Power plant base electricity production$_i$ = Power plant capacity factor$_i$ * power plant nameplate capacity$_i$ (both defined above) i = specific power plant (may be coal or natural gas-based) (U.S. EPA eGRID, 2007)
Levelized cost of electricity (LCOE) of CO_2 transport	¢/kWh	---	Annualized cost of CO_2 transport by formation / Power plant base electricity generation (defined above) Where: Annualized cost of CO_2 transport by formation = (Distance source to formations utilized * main pipeline capital cost per length + injection well field piping capital costs) * (saline formation capitalization factor (defined above) + O&M costs CO_2 pipeline as % capital)

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
			Main pipeline capital cost per length = Ogden L_o (reference pipeline) * mass of CO_2 to be sequestered (defined above)^Ogden Q weight * (distance source to formations utilized (defined above) / Ogden L_o)^ Ogden L weight * added pipeline capital cost for booster pumps (If > critical distance) * (U.S. GDP Historic Price Index Base / U.S. GDP Historic Price Index base for Ogden pipeline cost estimates) Assumptions for determining levelized cost for transporting CO_2: From Ogden (2002): "To model supercritical CO_2 pipelines, we use pipeline flow equations developed in Mohitpour et al. (2000) and Farris (1983). Published estimates of capital costs for CO_2 pipelines vary over more than a factor of two above and below the midrange value used here [Doctor, et al. (1999); Skovholt (1993); Holloway (1996); Ogden and Benson (2002); Fisher et al. (2002)]. Local terrain, construction costs and rights of way are all important variables in determining the actual installed pipeline cost. Using a cost function fit to published pipeline data, and inlet and outlet pressure of 15 MPa and 10 MPa, respectively, we find a pipeline capital cost per unit length (\$/m), in terms of the flow rate Q and the pipeline length L (Ogden and Benson, 2002): Cost (Q,L) = \$700m^{-1} * (Q/Qo)^0.48 * (L/L_o)^0.24 (Williams, 1998) Here Q_o = 16,000 tonnes*day^{-1} and Lo = 100 km … It is assumed that booster compressors are not needed for this 100 km pipeline. For transmission of more than 100 km, boosters might be needed."
Levelized cost of electricity (LCOE) for CO_2 injection	¢/kWh		Annualized cost of CO_2 injection wells / power plant base electricity generation (defined above) Where: Annualized cost of CO_2 injection wells = sequestration wells capital cost * (saline formation capitalization factor (defined above) + sequestration wells O&M costs as a % of capital) Where: sequestration wells O&M costs as a % of capital = 4%/year (Williams, 2002) Where: sequestration wells capital cost = either Ogden method * sequestration wells unused hole penalty factor OR MIT method * sequestration wells unused hole penalty factor

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
			Where: sequestration wells unused hole penalty factor = 1 + fraction of injection well capital for drilling only * (expected holes drilled per completed injection well - 1) Where: Ogden sequestration wells capital cost = (1,250,000 USD (Ogden, 2002) + sequestration depth * 1,560,000 USD (Ogden, 2002)) * number of injection wells * (U.S. GDP Historic Price Index Base / U.S. GDP Historic Price Index base for Ogden CO_2 injection well cost estimates) MIT sequestration wells capital cost = 0.0888* exp(0.0008 m^-1 * sequestration depth utilized) * number of injection wells * 1,000,000 USD * (U.S. GDP Historic Price Index Base / U.S. GDP Historic Price Index base for MIT drilling cost estimates) **Ogden method**: Ogden (2002) **MIT method**: Bock et al. (2002) Figure ES-2 gives the following relationship: Well Cost($M) = 0.0888e^(0.0008*Well Depth(m)) Assuming 1998 dollars
CO_2 injection costs per mass CO_2 sequestered	USD/tonne		Annualized cost of CO_2 injection wells (defined above) / mass of CO_2 to be sequestered (defined above)
Levelized cost of electricity (LCOE) for water extraction	¢/kWh		Annualized water extraction costs / power plant base electricity generation (defined above) Where: Annualized water extraction costs = Extraction wells capital cost * saline formation capitalization factor (defined above) + Extraction wells O&M Where: Extraction wells capital cost = Extraction well costs per depth & pumping rate * extraction well depth (defined above) * RO treatment plant capacity (defined earlier) * (U.S. GDP Historic Price Index base / U.S. GDP base for Well Cost Estimates) * Extraction well unused hole penalty factor Where: Extraction wells O&M = Extraction wells other O&M costs (defined above) + Extraction wells electricity O&M costs Where:

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
			Extraction wells electricity O&M costs = potential energy to extract water / (extraction well efficiency * make-up power LCOE)
Levelized cost of electricity (LCOE) for water transportation	¢/kWh		Annualized water transport costs by formation / power plant base electricity generation (defined above) Where: water pipeline capital costs * saline formation capitalization factor (defined above) + water pipeline O&M cost Where: water pipeline capital costs = water pipeline flow and distance cost change coefficient * RO treatment plant capacity (defined above) * distance source to formations utilized (defined above) + (Cost to move pure CO_2 pipeline distance change coefficient) * (U.S. GDP Historic Price Index base / U.S. GDP base for USBR 2003 costs) * Extraction well unused hole penalty factor Where: U.S. GDP base for USBR costs = year 2000. From Figure 9-11 of USBR (2003) as tabulated in Table B4 of Kobos et al. (2010a). Using data for 4,500 feet of pipeline only, the following parameters were developed: Cost to move pure CO_2 pipeline distance change coefficient is 111,314 $USD*mile^{-1}$ Water pipeline flow and distance cost change coefficient is 35,761 $USD*mile^{-1}*MGD^{-1}$ 

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
			Where: Water pipeline O&M cost = other pipeline O&M + cost of water pipeline electricity use Other pipeline O&M = water pipeline capital costs (defined above) * other O&M costs for water as a % of capital Other O&M costs for water as a % of capital = 1.5%*yr^{-1} Cappelle (2010) Where: Cost of water pipeline electricity use = potential energy to move extracted water / (water pipeline pump efficiency * levelized cost of make-up power (defined above))
Levelized cost of electricity (LCOE) for water treatment	¢/kWh		Annualized water treatment costs by formation / power plant base electricity generation (defined above) Where: Annualized water treatment costs by formation = RO plant capital costs * saline formation capitalization factor (defined above) + water treatment other O&M + RO chemical costs + RO plant electricity costs + RO plant labor costs + RO plant membrane replacement costs. Where: RO plant capital costs = choice of USBR RO plant capital costs OR Zammit and DiFilippo (2004) HERO plant capital costs USBR RO plant capital costs = (USBR RO Plant fixed capital costs + USBR RO plant variable capital costs * salinity average by formation (defined above) * RO treatment plant capacity (defined above)) * (U.S. GDP Historic Price Index base / U.S. GDP base for USBR (2003) costs) USBR RO plant fixed capital costs = 4.8 [Million $ 2000] USBR RO plant variable capital costs = 0.1 [Million $ 2000] * ppt^{-1} * MGD^{-1} Capital Cost [Million $ 2000] = 4.8 + 0.1*TDS[ppt]*Plant Capacity[MGD] At 10 ppt, this becomes 4.8 + Plant Capacity[MGD], essentially the same as the best fit line through the USBR brackish plant data: 5.1 + 1.01*Plant Capacity[MGD] And at 35 ppt, this becomes 4.8 + 3.5*Plant Capacity[MGD], very close to the best fit line through the USBR salt water plant data: 4.6 + 3.64*Plant Capacity[MGD] Referencing USBR (2003) and Cappelle (2010)

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
			DiFilippo HERO plant capital costs = (DiFilippo RO plant capital costs + DiFilippo treatment plant piping capital costs) * RO treatment plant inflow (defined above) * (U.S. GDP Historic Price Index base / U.S. GDP base for DiFilippo values) U.S. GDP base for DiFilippo value = 2004 from Table A-3 in Zammit and DiFilippo (2004) Where: RO plant labor costs = RO labor costs per treated water * RO treatment plant capacity (defined above)^RO labor costs exponent * (U.S. GDP Historic Price Index base / U.S. GDP base for USBR 2003 costs) RO labor costs per treated water = 171,778 $USD*yr^{-1}*MGD^{-1}$ RO labor costs exponent = 0.2322 Where: RO plant electricity costs = levelized cost of make-up power (defined above) * electricity use for RO (defined above) Where: RO plant membrane replacement costs = USBR membrane replacement constant * RO treated water stream (defined above) * (U.S. GDP Historic Price Index base / U.S. GDP base for USBR (2003) costs) USBR membrane replacement constant = 8 cents/1000 gallons USBR (2003) Where: RO chemical costs = choice of USBR chemical costs OR DiFilippo HERO chemical costs USBR chemical costs = USBR annual chemical costs constant * RO treatment plant capacity [Q capacity] (defined above) * (U.S. GDP Historic Price Index base / U.S. GDP base for USBR (2003) costs) USBR annual chemical costs constant = 38,800 $USD*yr^{-1}*MGD^{-1}$ Cost($M) = 0.0388 * Q capacity Equation developed by Cappelle (2010) DiFilippo HERO chemical costs = DiFilippo HERO plant chemical costs * RO treatment plant inflow capacity [Q capacity] (defined above) * (U.S. GDP Historic Price Index base / U.S. GDP base for DiFilippo values) DiFilippo HERO plant chemical costs = (392,000 $USD*yr^{-1}$ + 10000 $USD*yr^{-1}$) / 1316 $gallon*min^{-1}$

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
			Table A-3 from Zammit and DiFilippo (2004) Where: Water treatment other O&M = RO plant capital costs (defined above) * Other O&M costs for water as a % of capital (defined above)
Levelized cost (LCOE) for brine disposal – evaporation pond	¢/kWh		Annualized evaporation costs by formation / power plant base electricity generation (defined above) Where: Evaporation pond capital costs * saline formation capitalization factor (defined above) + evaporation pond O&M costs Where: Evaporation pond capital costs = (evaporation ponds capital variable cost per area * required area of evaporation ponds (defined above) + evaporation ponds capital fixed cost) * (U.S. GDP Historic Price Index base / U.S. GDP base for USBR (2003) costs) Evaporation ponds capital variable cost per area = 244,900 USD* $acre^{-1}$ Evaporation ponds capital fixed cost = 19,600 USD Both from figure 9-12 in USBR (2003) Evaporation pond O&M costs = evaporation pond capital costs (defined above) * other O&M costs for water as a % of capital (defined above)
Levelized cost (LCOE) for brine disposal - injection	¢/kWh		Annualized brine injection costs by formation / power plant base electricity generation (defined above) Where: Annualized brine injection costs by formation = (Brine injection pipeline capital cost + brine injection wells capital cost WECS method) * saline formation capitalization factor (defined above) + brine transport and injection total O&M Where: Brine injection pipeline capital cost = (pipeline flow and distance cost change cutoff (defined above) * brine concentrate stream (defined above) * distance from treatment to brine injection (defined above) + cost to move CO_2 pipeline distance change coefficient (defined above) * distance from treatment to brine injection (defined above)) * (U.S. GDP Historic Price Index base / U.S. GDP base for USBR 2003 costs)

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
			Brine injection wells capital cost WECS method = (brine injection well cost per rate * RO treatment plant capacity (defined above) + brine injection well fixed cost) * U.S. GDP Historic Price Index base / U.S. GDP base for USBR (2003) costs – brine injection pipeline capital cost (defined above) Brine injection well cost per rate = 194,893 USD*MGD^{-1} Brine injection well fixed cost = 2,359,271 USD Kobos (2010a) Appendix B referring to USBR (2003) Table 18 (Figure 9-13). Equation developed is: Cost = 194,893 ($/desal capacity) * Desal Capacity + $2,359,271 Brine transport and injection total O&M = brine transport and injection other O&M + electricity costs for brine transport for injection Brine transport and injection other O&M = brine injection pipeline capital cost (defined above) + brine injection wells capital cost WECS method (defined above) * other O&M costs for water as a % of capital (defined above) Electricity costs for brine transport and injection = potential energy to move brine for injection (defined above) * levelized cost of makeup power (defined above)
Levelized cost (LCOE) for brine disposal – free disposal	¢/kWh		Annualized brine transport to free disposal by formation / power plant base electricity generation (defined above) Where: Annualized brine transport to free disposal by formation = brine pipeline for free disposal capital cost * saline formation capitalization factor (defined above) + brine transport for free disposal total O&M Where: Brine pipeline for free disposal capital cost = pipeline flow and distance cost change coefficient (defined above) * brine concentrate stream (defined above) * default distance from power plant to free brine disposal (defined above) + cost to move pure CO_2 pipeline distance change coefficient (defined above) * default distance from power plant to free brine disposal (defined above) * (U.S. GDP Historic Price Index base / U.S. GDP base for USBR 2003 costs) Brine transport for free disposal total O&M = brine pipeline for free disposal other O&M + electricity costs for brine transport for free disposal Electricity costs for brine transport for free disposal = potential energy to move brine for free disposal (defined above) * levelized cost of make-up power (defined above)

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
			Brine pipeline for free disposal other O&M = brine pipeline for free disposal capital cost (defined above) * other O&M costs for water as a % of capital (defined above)
Levelized cost (LCOE) for brine disposal – brine concentrator	¢/kWh		Annualized brine concentrator disposal costs / power plant base electricity generation (defined above) Where: Brine concentrator capital cost * saline formation capitalization factor (defined above) + brine concentrator electricity use * levelized cost of make-up power (defined above) + brine concentrator other O&M + brine concentrator chemical costs Where: Brine concentrator capital cost = brine concentrator capital cost intercept + brine concentrator capital cost slope * brine concentrate stream (defined above) * (U.S. GDP Historic Price Index base / U.S. GDP base for AWWA (2007) costs) Brine concentrator capital cost intercept = 1,051,500 USD Brine concentrator capital cost slope = 7,422,000 USD*MGD^{-1} Cappelle (2010) Base year for AWWA costs = 2004 Table 3-16 in AWWA (2007) Brine concentrator electricity use = brine concentrate stream (defined above) * brine concentrator electricity use per concentrate stream Brine concentrator electricity use per concentrate stream = 34,429,592 kWh*yr-1*MGD^{-1} Figure 3 from Cappelle (2010) Brine concentrator other O&M = brine concentrator capital cost (defined above) * Other O&M cost for water as a % of capital (defined above) Brine concentrator chemical costs = brine concentrate stream (defined above) * brine concentrator chemical cost * (U.S. GDP Historic Price Index base / U.S. GDP base for DiFilippo values) Brine concentrator chemical cost = 7,000 USD*yr^{-1} / 329 gallon*min^{-1}. This is based on the Zammit and DiFilippo (2004) chemical costs of $7,000 per year associated with brine concentrator cleaning. The feed rate for this study was 1,316 gallons per minute into the 75% efficient RO plant resulting in 329 gpm concentrate flows. Thus the annual BC chemical costs can be estimated at $7,000/329 gpm

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
Annualized costs by formation and brine disposal method	USD/yr	Total annualized cost for CCS with water extraction, treatment and disposal	Annualized costs of CO_2 transport and sequestration + annualized costs of water production and treatment + annualized costs of brine disposal by formation and method
Marginal LCOE due to CCS	¢/kWh	Used to determine the LCOE for CO_2 capture and storage for an individual formation	Marginal LCOE due to CCC + Marginal LCOE due to CS Where: Marginal LCOE due to CCC = marginal LCOE due to make-up power requirements + LCOE CCC without make-up power (defined above) Marginal LCOE due to make-up power requirements = (LCOE of make-up power (defined above) * parasitic energy requirements (defined above)) / power plant base electricity generation (defined above) Where: Marginal LCOE due to CS = marginal LCOE due to CO_2 injection + marginal LCOE due to CO_2 transport Marginal LCOE due to CO_2 injection = LCOE of CO_2 injection (defined above) Marginal LCOE due to CO_2 transport = LCOE of CO_2 transport] (defined above)
Marginal LCOE due to water production, treatment and brine disposal	¢/kWh	Used to determine the LCOE for water production, treatment and brine disposal method for an individual formation	Marginal LCOE due to water production transport & treatment + marginal LCOE due to brine disposal Where: Marginal LCOE due to water production transport & treatment = LCOE water extraction (defined above) + LCOE water transport (defined above) + LCOE water treatment (defined above) LCOE water treatment = choice between evaporation pond, free disposal via pipeline, injection and concentrator Where: Marginal LCOE due to brine disposal = choice of LCOE brine disposal OR LCOE of evaporation ponds OR LCOE of brine injection OR LCOE of brine concentrator (all defined above)
Total LCOE from CCS and water production, treatment and brine disposal	¢/kWh		Base power plant LCOE (defined above) + marginal LCOE due to CCS (defined above) + marginal LCOE due to water production, treatment and brine disposal (defined above)

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
LCOE percent change due to CCS	%		(LCOE including CCS and water production, treatment and brine disposal – base power plant LCOE) / base power plant LCOE Where: LCOE including CCS and water production, treatment and brine disposal = (base power plant LCOE (defined above) + marginal LCOE due to CCS (defined above)) + marginal LCOE due to water production, treatment, and brine disposal (defined above)
Total CCS costs per mass CO_2 sequestered	USD/tonne	Sum of all costs for CCS as a function of the mass of CO_2 sequestered	Costs of CCC per mass of CO_2 sequestered + cost of CO_2 transport per mass of CO_2 sequestered + cost of CO_2 injection per mass of CO_2 sequestered + cost of water production, transport and treatment per mass of CO_2 sequestered + cost of brine disposal per mass of CO_2 sequestered Where: Cost of CCC per mass of CO_2 sequestered = (marginal LCOE due to CCC) * power plant base electricity generation (defined above)) / mass of CO_2 to be sequestered (defined above) Cost of CO_2 transport per mass of CO_2 sequestered = (marginal LCOE due to CO_2 transport (defined above)) * power plant base electricity generation (defined above)) / mass of CO_2 to be sequestered (defined above) Cost of CO_2 injection per mass of CO_2 sequestered = (marginal LCOE due to CO_2 injection (defined above)) * power plant base electricity generation (defined above)) / mass of CO_2 to be sequestered (defined above) Cost of water production, transport & treatment per mass of CO_2 sequestered = (marginal LCOE due to water production, transport & treatment (defined above)) * power plant base electricity generation (defined above)) / mass of CO_2 to be sequestered (defined above) Cost of brine disposal per mass of CO_2 sequestered = (marginal LCOE due to brine disposal (defined above)) * power plant base electricity generation (defined above)) / mass of CO_2 to be sequestered (defined above)
Total CCS costs per mass CO_2 kept out of atmosphere	USD/tonne	Sum of all costs for CCS as a function of the mass of CO_2 not released into the atmosphere	Cost of CCC per mass reduction atmospheric CO_2 emissions + Cost of CO_2 transport per mass reduction atmospheric CO_2 emissions + Cost of CO_2 injection per mass reduction atmospheric CO_2 emissions + Cost of water production, transport & treatment per mass reduction atmospheric CO_2 emissions + Cost of brine disposal per mass reduction atmospheric CO_2 emissions Where: Cost of CCC per mass reduction atmospheric CO_2 emissions = (Marginal LCOE due to CCC (defined above) * power plant base electricity generation (defined above)) / reduced emissions to atmosphere (defined above)

Parameter	Unit(s)	Description	Equation, Assumption, and/or Source
			Cost of CO_2 transport per mass reduction atmospheric CO_2 emissions = (Marginal LCOE due to CO_2 transport (defined above) * power plant base electricity generation (defined above)) / reduced emissions to atmosphere (defined above) Cost of CO_2 injection per mass reduction atmospheric CO_2 emissions = (Marginal LCOE due to CO_2 injection (defined above) * power plant base electricity generation (defined above)) / reduced emissions to atmosphere (defined above) Cost of water production, transport & treatment per mass reduction atmospheric CO_2 emissions = (Marginal LCOE due to water production, transport & treatment (defined above) * power plant base electricity generation (defined above)) / reduced emissions to atmosphere (defined above) Cost of brine disposal per mass reduction atmospheric CO_2 emissions = (Marginal LCOE due to brine disposal (defined above) * power plant base electricity generation (defined above)) / reduced emissions to atmosphere (defined above)

APPENDIX B: NATCARB POLYGON DEVELOPMENT

The first step in developing the saline formation database consisted of delineating the projected map-view surface area of the desired saline formations within the contiguous U.S. Using the spatial representations of saline formations from the 2008 NatCarb Atlas (supplemental geospatial data) (NETL, 2008) as a starting point, over 10,000 individual features were analyzed to create a database of 325 saline formation 'polygons.' In many cases, the polygon representation of a saline formation was merged due to previous divisions based on state lines. Other polygons were merged from hundreds of small features into one feature. As can be seen in Figure B-1, there are many aerially overlapping formations due to different depths of the formations, with some formations located on the continental shelf. Political boundaries mirrored for some saline formations shown in Figure B-1 are a result of the division of defined study areas into the seven regional partnerships and/or the lack of data to determine an exact formation boundary. In some cases basins are estimated, as more detailed formation information within that basin is not available.

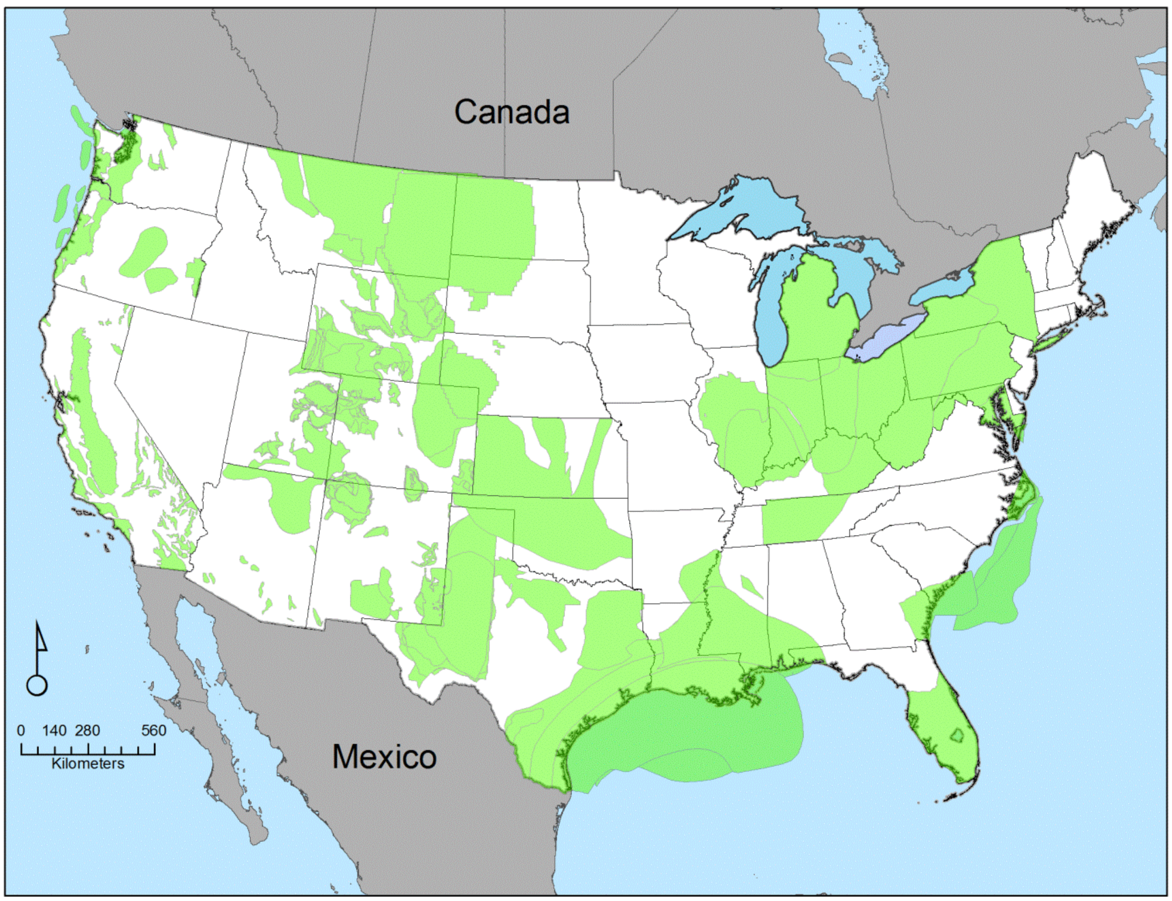


Figure B-1. Location map of the 325 polygons representing saline formations used in WECSsim.

APPENDIX C: NATCARB POLYGON SHAPE SIMPLIFICATION

Because the NatCarb 2008 database described in Appendix B is a geospatial database, the area of the polygons is implicitly defined for all polygons. As it turned out, this two dimensional area and CO_2 storage estimates were the only parameters for which a value was available for every polygon derived from the publically available NatCarb 2008 database. However, despite data availability, the polygon shapes were processed further in order to include simplified shape information in WECSsim. That process is described here.

C.1 Motivation for Simplified Representation of Polygon Shapes

Powersim Studio 9 (Powersim) with version 7 compatibility, the software used to develop WECSsim, does not have strong geospatial data representation capabilities. To represent two-dimensional geospatial data in WECSsim, shapes were simplified to nine points: a centroid and eight points around the centroid at the cardinal and ordinal directions. The eight points surrounding the centroid are referred to as rose points throughout this appendix because they are defined by the compass rose. This appendix describes the process used to simplify the polygons from the NatCarb database for use in WECSsim.

C.2 NatCarb 2008

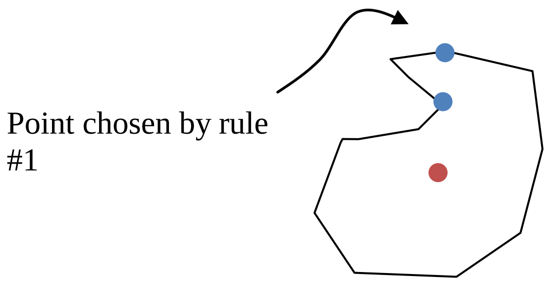
As discussed in Appendix B, the NatCarb 2008 saline formation geospatial database was the original source of the data for this process. The original database has approximately 10,000 saline formation ‘features’ in the U.S. and Canada. These were combined into 325 individual polygon features limited to the continental U.S., including offshore areas. Many of the formations in the original dataset were broken up by state line, and others represented gridded data that were merged into contiguous saline formations. The combination of features did not reduce the available hydrogeologic information, but it did repackage it in a form more suited to our U.S. specific analysis.

After processing the data into the 325 individual formations as described in Appendix B, an ArcGIS function was used to export the centroids of each polygon to a Microsoft Excel (Excel) file with a corresponding unique ID. A different function was used to convert each formation polygon into a set of points using the vertices that define the shape of the polygon. The data were also exported to Excel and have a unique ID that match the centroid’s unique ID.
An exhaustive search of functions and tools in ArcGIS was conducted to take the centroid of the polygon and extend it out to find the points on the polygon in eight cardinal/ordinal directions that roughly define its shape. There was not a function available to process the data in an automated fashion, so Matlab scripts were created for determining these point coordinates.

C.3 Simplification of the Shapes

Matlab was used to process the different points generated by the GIS process described above. Those points are referred to as border points here. The number of border points generated by the GIS process for each shape varied from a minimum of eight to a maximum of 20,723. To handle the shapes defined by a small number of points, a fairly robust process was needed. The following rules were adopted:

1. Find the point within +/- x degrees of the desired direction that is farthest from the centroid. The idea here is to try to capture some of the waviness of a figure, or areas where a figure may double back. For example, consider the following figure in which the red point is the hypothetical centroid, and the blue points are both within x degrees of north of the centroid. For the simplified shape, the analysis takes the point further from the centroid.



2. If there is no point within +/- x degrees of the direction in question, find the point closest to the direction in question within +/- y degrees.

3. If there is no point within +/- y degrees of the direction, choose the centroid. This rule ends up being applied in situations where the border points are very sparse, or the centroid is actually external to the shape. Initially, only internal centroids were used, but the results were less satisfying than when using external centroids and allowing the centroid to act as a border point, essentially meaning the shape would not extend at all in that direction.

4. The distances of the selected points were then calculated and used as the distances from the centroid to the edge of the shape in the eight cardinal and ordinal directions, which defines the simple shape.

These rules were implemented in Matlab and applied to the 325 formation shapes from the NatCarb 2008 database. The parameters “x” and “y” are referred to as tolerance and sweep, and do influence the resulting shapes created in this process. Visual trial and error resulted in the use of 7.5 and 30 degrees for tolerance and sweep, respectively. In general, the more round a shape, the better this process works, and the more long and thin, the worse. The eight points chosen are called the rose points from the idea of a compass rose, and the distance from the centroid to the compass point, along with the cardinal or ordinal direction in which that point occurs define the simplified shape. Thus, the simple shape does not necessarily intersect the rose points. Some representative shapes and their simple shape equivalents are shown in Figures C-1, C-2, and C-3 below. Similar figures are available for all of the 325 formations used.

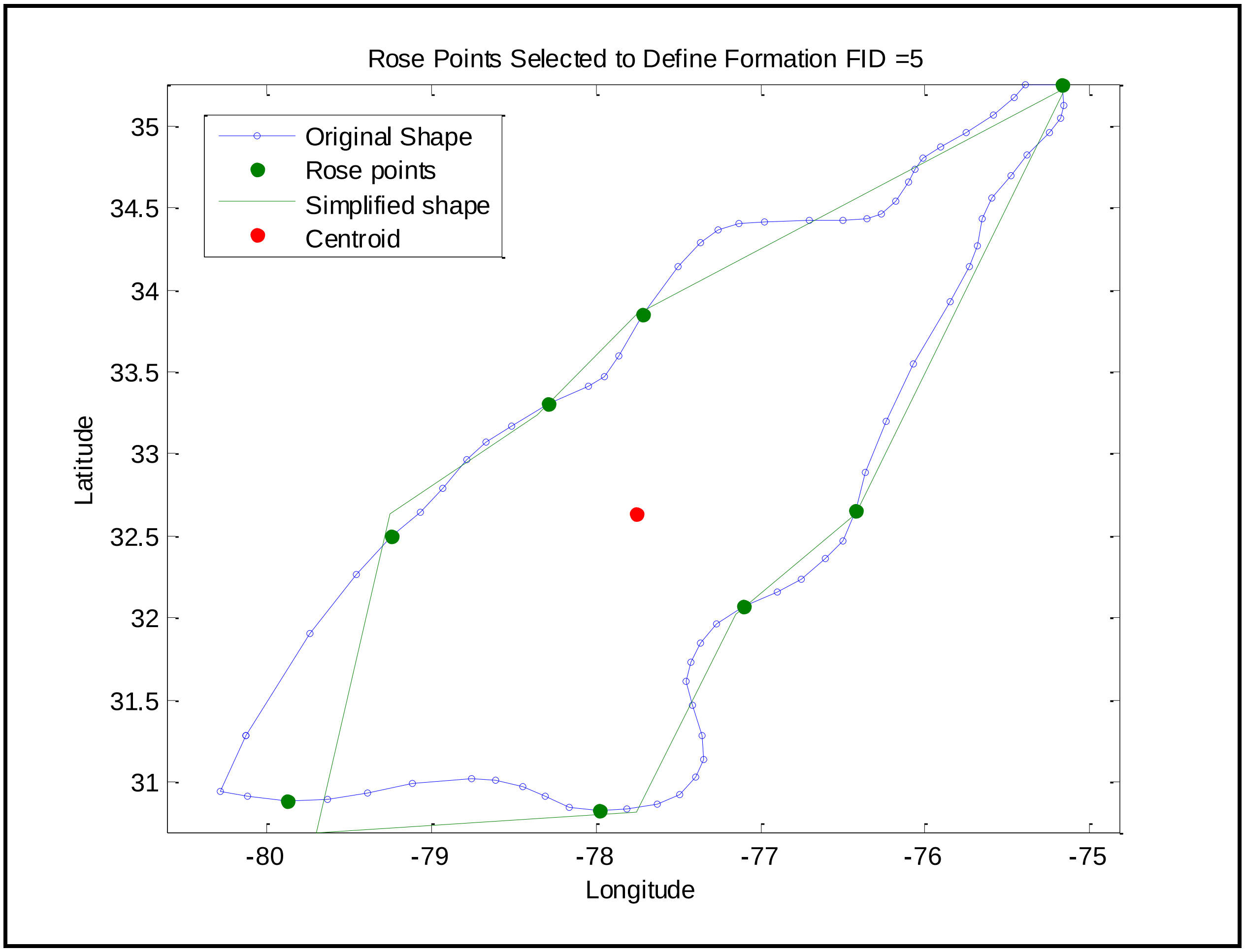


Figure C-1. The rose points and simplified shape for the illustrative formation with FID=5.

Note: This simplification worked fairly well, except in the bottom left corner because the extent of the bulge is north of SW. The simplified shape doesn't necessarily correspond to the border points because the border point is used to determine a distance which the simplified shape takes in one of the eight cardinal/ordinal directions. Where selected border points are not in the exact direction considered, they will not fall on the edge of the simplified shape. The simplified shape can also intersect a point in the original polygon perfectly because the first of the rules is to select the point farthest away within a given tolerance.

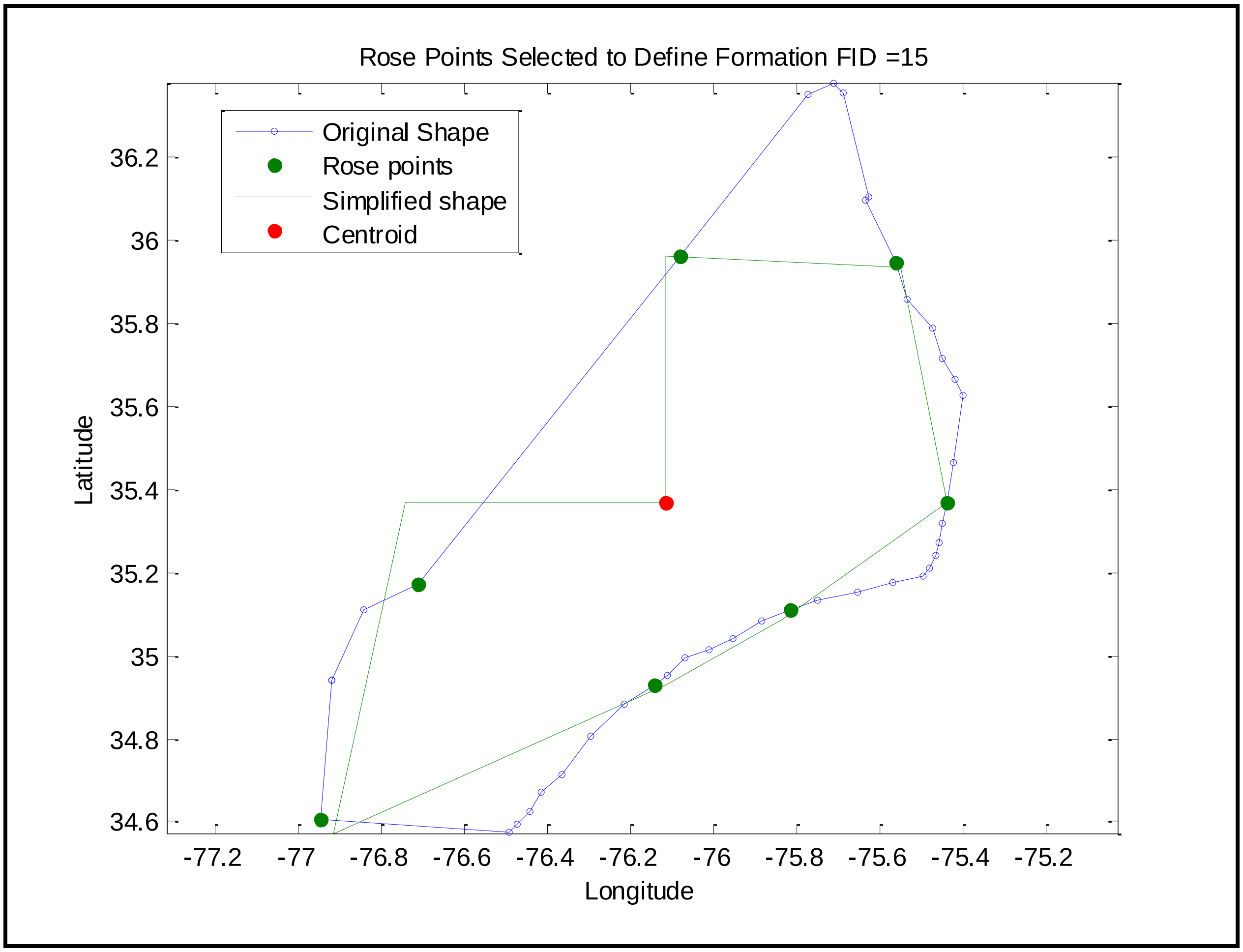


Figure C-2. The rose points and simplified shape for the illustrative formation with FID=15.

Note: This is an example of a shape for which the simplification worked poorly due to a lack of points generated by the GIS routine to define the original shape. This shape shows the result of a lack of points in the NW sweep resulting in use of the centroid for that rose point. A higher tolerance (x) parameter would result in the points at the top of the original shape being selected for the N and NE directions, and thus a larger simplified shape, but not necessarily a more accurate simplification.

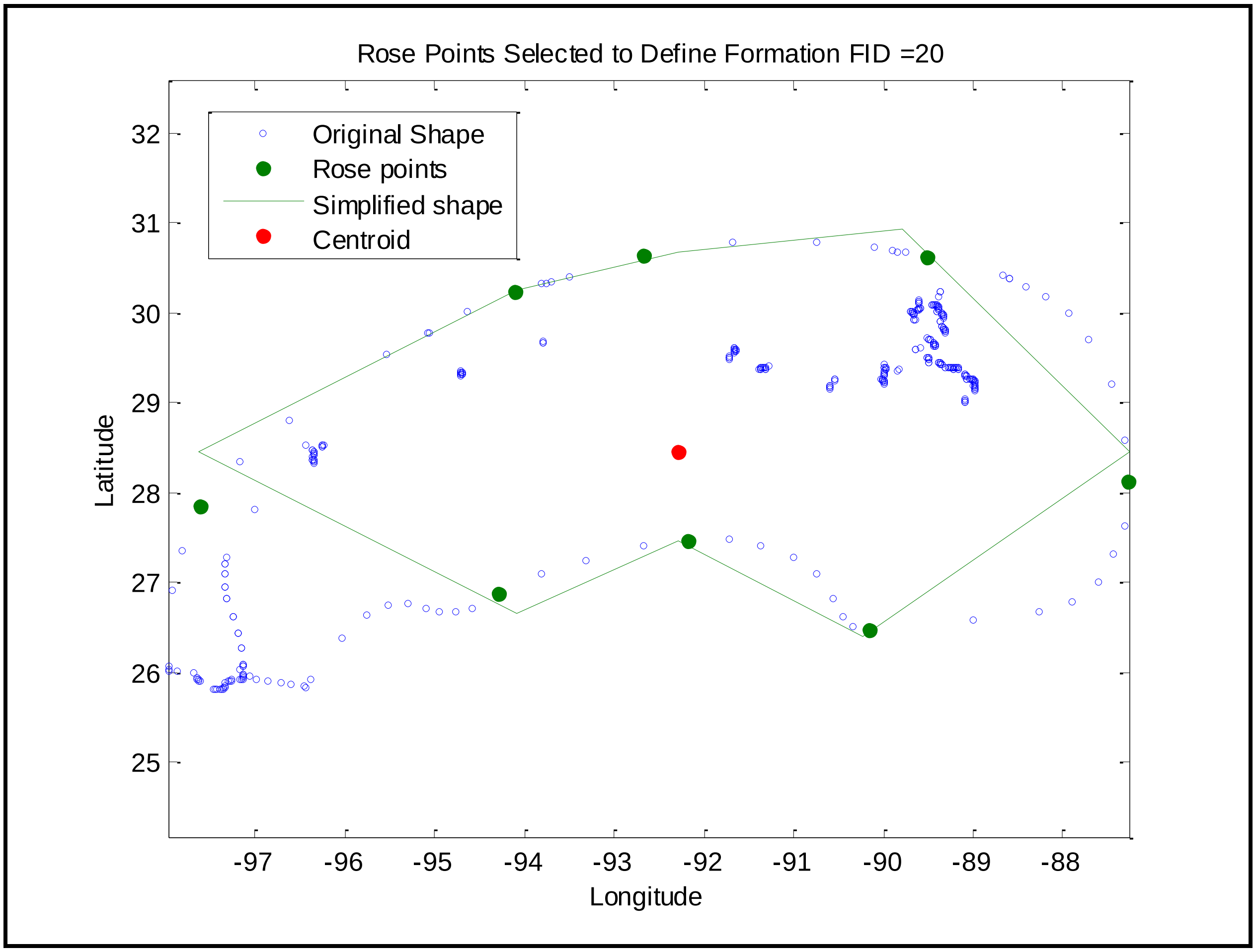


Figure C-3. The rose points and simplified shape for the illustrative formation with FID=20.

Note: From an absolute area perspective, this is the worst simplification of all, with the simplified shape 31,000 square miles smaller than the GIS shape (see Figure C-4), though from a percent error perspective, the simplification represents a more reasonable 22% reduction in area. The reason for border points internal to the overall shape may deserve further analysis.

The areas of the simplified shapes are compared to the areas of the GIS shapes in Figure C-4 below, and the distribution of % error is shown in Figure C-5. As can be seen Figure C-4, the overall agreement is good, and there is not any overall bias to area resulting from simplification in this manner. As can be seen from Figure C-5, the simplified area is within 10% of the GIS area for 44% of the shapes, within 20% for 72% of the shapes, and within 30% for 86% of the shapes. Considering the uncertainty associated with delineation of these deep saline formations to begin with, these results are acceptable and show that substantial simplification can occur without critical loss of information needed for a system's level analysis of the formations.

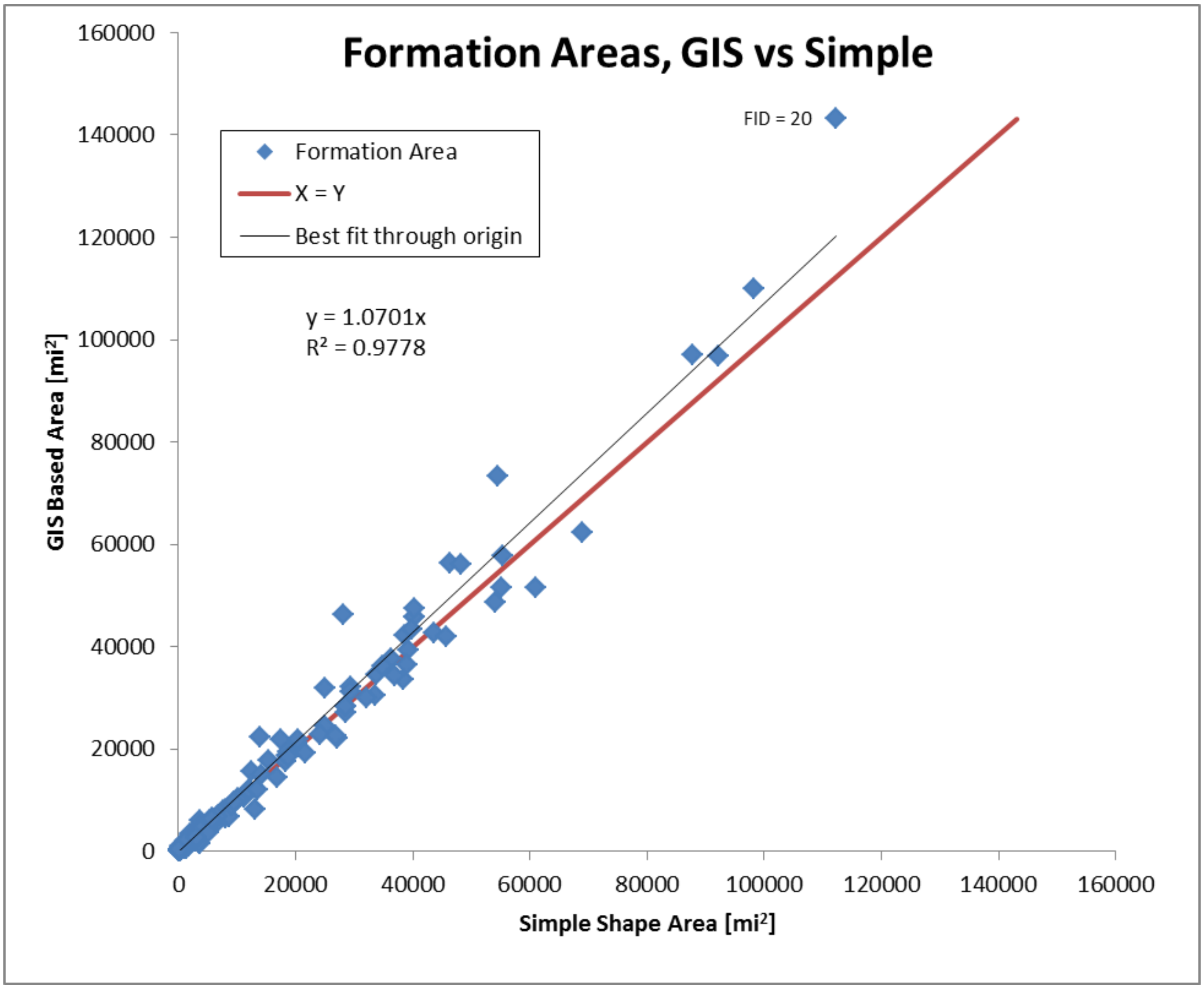


Figure C-4. Scatter plot comparison of the area of the simplified shape and the area of the GIS polygon of the original formation.

Note: The overall agreement is good, and there is not any overall bias to area resulting from simplification. In terms of absolute error, the worst formation is FID=20, which can be seen in Figure C-3.

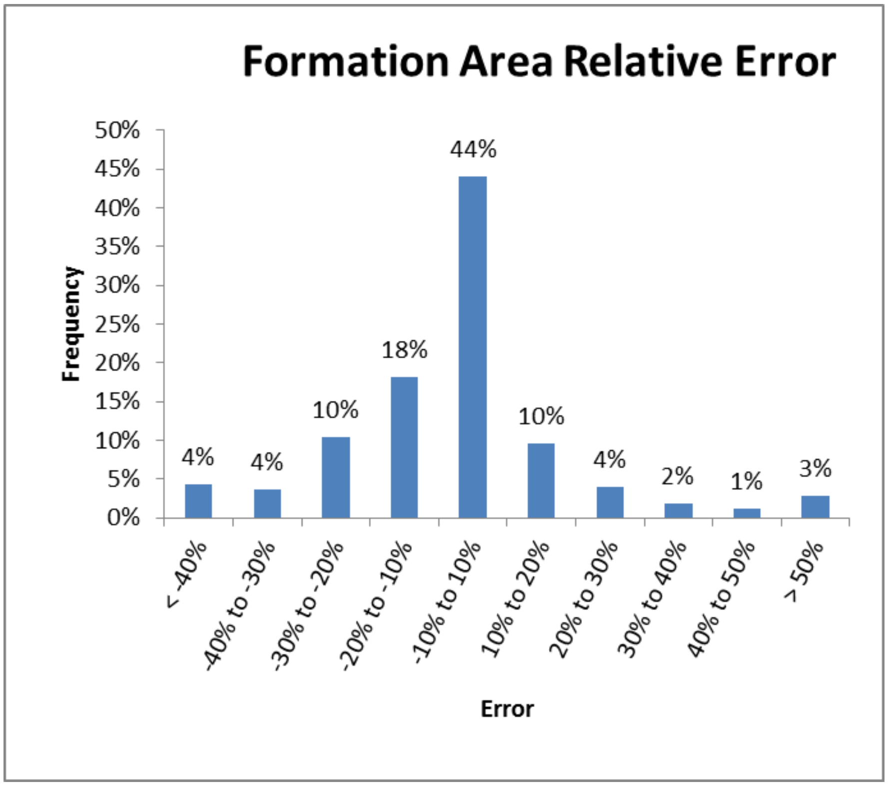


Figure C-5. Histogram of the relative boundary error for the deep saline formations.
Note: Only 14% of shapes have a relative error greater than +/- 30%. The simplified area is within 10% of the GIS area for 44% of the shapes, within 20% for 72% of the shapes, and within 30% for 86% of the shapes. Considering the uncertainty associated with delineation of these deep saline formations to begin with, these results are reasonable.

The end result of this process is eight distances for each of the 325 formations being considered. These distances, together with a centroid, represent the approximate shape of a saline formation in the NatCarb database and are the shapes used in WECSsim. This simple geospatial representation is data light and easily implemented in the WECSsim model itself, and though it does represent a loss of information, the magnitude of this information loss from the perspective of a national-scale systems model is thought to be well within the error associated with the original data. For each formation, the simplified geometry used by WECSsim including the latitude and longitude of the centroid point and the distance from that point to the edge of the formation in each of the cardinal and ordinal directions is shown in Table C-1, which occupies the remainder of this appendix.

Table C-1. Simplified shape information for the 325 NatCarb 2008 based polygons used in WECSsim.

FID	PARTNER-SHIP	BASIN NAME	FORMATION	Centroid		Distance From Centroid to Edge of Formation in Given Direction [miles]							
				Longitude	Latitude	N	NE	E	SE	S	SW	W	NW
0	SECARB	Cedar Keys Lawson Fm	Cedar Keys Lawson Fm	-81.3373	27.2676	155	71	83	125	146	76	78	140
1	SECARB	GULF COAST	Eocene Sand	-93.8995	29.9930	116	192	446	0	0	389	253	147
2	SECARB	GULF COAST	Tertiary Undivided	-90.7107	32.7953	149	55	62	134	90	85	50	136
3	SECARB	GULF COAST	Oligocene	-94.5436	29.2844	109	174	269	0	0	322	185	100
4	SECARB	Tuscaloosa Group	Tuscaloosa Group	-89.8986	31.6843	107	87	199	139	81	78	201	143
5	SECARB	Offshore Atlantic	not available (n/a)	-77.7558	32.6304	84	236	77	54	125	173	87	56
6	SECARB	Offshore Atlantic	n/a	-78.0314	33.2898	8	110	36	13	19	141	15	0
7	SECARB	Woodbine & Paluxy Fm	Woodbine & Paluxy Fm	-95.4392	32.1206	101	123	83	89	114	128	73	96
8	MGSC	Illinois Basin	Cypress SS	-88.3603	38.3326	56	42	25	35	41	44	26	30
9	MGSC	Illinois Basin	Mt. Simon SS	-88.4385	39.2665	131	109	132	165	141	126	131	184
10	MGSC	Illinois Basin	St. Peter SS	-88.0984	38.6002	101	103	92	115	96	105	95	110
11	SECARB	GULF COAST	Olmos	-99.2641	28.5018	26	49	42	15	11	57	30	28
12	SECARB	GULF COAST	Pliocene	-91.3327	27.4016	23	52	199	82	79	105	280	26
13	SECARB	Potomac Group	Potomac Group1	-75.5656	37.8466	11	16	16	0	21	0	13	10
14	SECARB	Potomac Group	Potomac Group2OS	-75.4539	37.6499	14	32	0	0	21	12	5	6
15	SECARB	Potomac Group	Potomac Group2	-76.1163	35.3694	41	51	38	25	30	71	36	0
16	SECARB	Potomac Group	Potomac Group1OS	-75.6727	35.2288	61	34	12	15	5	65	0	0
17	SECARB	Pottsville Fm	Pottsville Fm	-89.1285	33.4923	21	11	17	49	0	0	19	37
18	SECARB	South Carolina-Georg	Triassic, Tuscaloosa	-80.6737	32.0116	51	98	99	65	103	115	103	61
19	MRCSP	Coastal Plains	n/a	-76.2379	38.7318	62	49	29	68	48	46	54	44
20	SECARB	GULF COAST	Miocene	-92.2787	28.4499	153	226	305	188	68	163	326	166
21	SECARB	Mt. Simon SS	Mt. Simon SS	-86.5325	35.8848	0	152	118	71	0	118	106	100
22	MRCSP	Michigan Basin	n/a	-84.7560	43.1798	180	149	119	113	152	175	86	136
23	MRCSP	Appalachian Basin	n/a	-80.4777	40.1161	137	295	106	96	190	338	143	130
24	MRCSP	Fold and Thrust Belt	n/a	-75.6562	41.8228	210	239	113	118	148	304	41	118
25	Big Sky	Montana Thrust Belt	Imbricate Thrust Gas	-113.2479	47.9600	72	32	31	114	62	36	32	94
26	Big Sky	North-Central Montana	Jurassic-Cretaceous	-109.4042	47.5418	101	134	94	145	104	107	141	134
27	Big Sky	North-Central Montana	Shallow Cretaceous B	-109.0061	47.4923	105	135	76	156	137	72	138	138
28	Big Sky	Southwest Montana	Crazy Mountains and	-109.7513	45.8220	30	45	41	46	27	27	58	43
29	Big Sky	Southwest Montana	Nye-Bowler Wrench Zo	-109.5781	45.3447	4	3	43	9	0	0	9	7
30	Big Sky	Big Horn Basin	Deep Basin Structure	-108.4658	44.3474	21	17	21	41	28	21	19	59
31	Big Sky	Big Horn Basin	Phosphoria Stratigra	-107.9138	44.1431	45	6	6	15	43	11	9	16
32	Big Sky	Wind River Basin	Basin Margin Subthru3	-109.3774	43.6323	4	3	7	13	5	4	6	11
33	Big Sky	Wind River Basin	Basin Margin Subthru	-107.4642	43.2405	14	14	21	54	0	0	57	19
34	Big Sky	Wind River Basin	Basin Margin Subthru2	-107.9337	42.5799	6	3	3	17	7	5	6	16
35	Big Sky	Wind River Basin	Basin Margin Anticli	-108.7909	43.2133	25	23	0	47	19	12	2	29

FID	PARTNER-SHIP	BASIN NAME	FORMATION	Centroid		Distance From Centroid to Edge of Formation in Given Direction [miles]							
				Longitude	Latitude	N	NE	E	SE	S	SW	W	NW
36	Big Sky	Wind River Basin	Basin Margin Anticli2	-107.9482	42.9052	8	11	32	9	8	21	26	18
37	Big Sky	Wind River Basin	Deep Basin Structure	-107.9940	43.1737	14	19	45	14	10	10	46	23
38	Big Sky	Wind River Basin	Muddy Sandstone Stra	-107.8525	42.8566	11	18	54	3	3	28	44	19
39	Southwest	Permian	Montoya	-102.5805	31.5983	128	120	77	110	83	89	124	39
40	MRCSP	Arches Province	n/a	-84.8345	39.7563	93	167	90	125	161	91	86	141
41	Big Sky	North-Central Montana	Fractured-Faulted Ca	-109.4042	47.5418	101	134	94	145	104	107	141	134
42	Big Sky	North-Central Montana	Tyler Sandstone	-108.2406	46.4021	53	41	103	38	82	61	111	60
43	Southwest	Permian	Pennsylvanian	-102.0383	33.2089	210	130	67	97	205	151	187	128
44	Southwest	Permian	San Andres	-101.9423	32.5569	133	113	61	102	142	107	65	91
45	Southwest	Permian	Siluro-Devonian	-102.8225	31.5636	179	112	107	139	82	146	133	34
46	Big Sky	Wyoming Thrust Belt	Hogsback Thrust	-110.6031	41.6312	59	22	10	11	47	21	4	6
47	Big Sky	Wyoming Thrust Belt	Cretaceous Stratigra	-110.6823	41.5196	26	12	5	5	25	13	3	2
48	Big Sky	Southwestern Wyoming	Rock Springs Uplift	-108.8878	41.6353	36	24	30	19	34	32	20	29
49	Big Sky	Southwestern Wyoming	Cherokee Arch	-108.2428	40.9796	6	8	42	9	0	11	40	7
50	Big Sky	Southwestern Wyoming	Moxa Arch-LaBarge	-110.1237	41.8742	48	24	9	16	59	10	5	23
51	Big Sky	Southwestern Wyoming	Basin Margin Anticli	-109.0919	42.5470	0	0	82	33	21	18	71	72
52	Big Sky	Southwestern Wyoming	Basin Margin Anticli2	-110.3688	41.4326	50	17	9	18	35	32	7	8
53	Big Sky	Southwestern Wyoming	Basin Margin Anticli3	-109.5972	40.9980	2	3	33	0	0	0	35	4
54	Big Sky	Southwestern Wyoming	Basin Margin Anticli4	-108.6276	40.7968	6	2	2	14	4	3	5	11
55	Big Sky	Southwestern Wyoming	Platform	-106.5384	41.6384	42	55	55	61	15	75	51	59
56	Big Sky	Williston Basin	Madison (Mississippi	-104.5840	47.1414	129	53	26	166	133	59	72	172
57	Big Sky	Williston Basin	Red River (Ordovicia	-104.5840	47.1414	129	53	26	166	133	59	72	172
58	Big Sky	Williston Basin	Middle and Upper Dev	-104.5840	47.1414	129	53	26	166	133	59	72	172
59	Big Sky	Williston Basin	Pre-Prairie Middle D	-105.2013	47.8724	78	94	55	116	90	58	60	103
60	Big Sky	Williston Basin	Post-Madison through	-105.2782	48.1419	59	79	58	105	69	56	65	78
61	Big Sky	Williston Basin	Pre-Red River Gas	-104.4070	48.3314	46	34	17	34	59	26	17	55
62	Big Sky	Powder River Basin	Basin Margin Anticli	-106.0889	43.8913	0	0	108	117	86	70	35	170
63	Big Sky	Powder River Basin	Leo Sandstone	-105.1007	43.4328	50	49	46	33	49	51	48	34
64	Big Sky	Powder River Basin	Upper Minnelusa Sand	-105.7158	44.4247	63	78	45	54	102	59	54	55
65	Big Sky	Powder River Basin	Lakota Sandstone	-105.6363	44.4021	96	81	51	101	110	64	65	109
66	Big Sky	Powder River Basin	Fall River Sandstone	-105.2893	44.1745	111	71	43	78	100	97	20	106
67	Southwest	Permian	Simpson	-102.7716	31.2862	100	77	89	116	62	73	122	101
68	Big Sky	Wind River Basin	Shallow Tertiary - U	-107.9607	43.1010	18	25	47	18	16	34	47	32
69	Big Sky	Wyoming Thrust Belt	Moxa Arch Extension	-110.6203	42.8655	26	5	4	11	27	5	4	9
70	Big Sky	Wyoming Thrust Belt	Absaroka Thrust	-110.9611	41.5692	65	39	15	15	48	67	8	8
71	Big Sky	North-Central Montana	Devonian-Mississippi	-109.4467	47.5186	103	136	97	143	102	105	140	135

FID	PARTNER-SHIP	BASIN NAME	FORMATION	Centroid		Distance From Centroid to Edge of Formation in Given Direction [miles]							
				Longitude	Latitude	N	NE	E	SE	S	SW	W	NW
72	Southwest	Permian	San Andres Limestone	-103.6388	32.9047	42	52	36	32	45	43	40	35
73	Southwest	Permian	Triassic	-102.1159	32.6641	141	111	86	92	143	120	110	129
74	Southwest	Permian	Upper_Guadalupe	-102.4144	31.9682	130	130	89	127	98	112	139	94
75	Southwest	Permian	Wolfcamp	-101.9468	33.5588	187	100	68	114	215	136	0	136
76	Southwest	Permian	Morrison Formation	-103.5566	32.9395	45	47	32	55	39	36	47	48
77	Big Sky	Powder River Basin	Muddy Sandstone	-105.6426	44.3703	98	83	53	100	113	62	64	110
78	Big Sky	Powder River Basin	Deep Frontier Sandst	-105.6169	43.3786	30	31	37	55	42	30	21	89
79	Big Sky	Powder River Basin	Turner Sandstone	-104.7192	43.6919	38	26	30	35	44	23	28	39
80	Big Sky	Powder River Basin	Sussex-Shannon Sands	-105.9105	44.1292	72	37	44	83	88	36	27	93
81	Big Sky	Powder River Basin	Mesaverde-Lewis	-105.9138	43.9760	76	36	22	97	75	26	33	99
82	Southwest	Navajo Power Plant	CEDAR MESA SANDSTONE	-111.3733	36.8173	9	7	9	7	6	8	10	4
83	Southwest	Cholla Power Plant	NACO	-110.3056	34.9354	8	8	7	7	7	7	7	8
84	Southwest	St. Johns-Springervi	GRANITE WASH	-109.1977	34.3262	7	5	5	14	7	0	6	13
85	Southwest	Willcox basin	TERTIARY BASIN FILL	-109.8508	32.2086	14	5	5	16	17	8	6	16
86	Southwest	Red Rock basin	TERTIARY BASIN FILL	-111.2795	32.5391	21	2	3	9	20	7	6	7
87	Southwest	Higley basin	TERTIARY BASIN FILL	-111.7246	33.3059	8	7	12	10	6	9	10	10
88	Southwest	Luke basin	BASIN FILL-EVAPORITE	-112.2978	33.5235	9	5	12	11	9	8	9	13
89	Southwest	Tucson basin	TERTIARY EVAPORITES-	-110.8735	32.0036	18	12	10	7	14	18	4	10
90	Southwest	Mohawk basin	TERTIARY BASIN FILL	-113.8296	32.6050	11	6	8	14	11	8	7	15
91	Southwest	San Cristobal basin	TERTIARY BASIN FILL	-113.5463	32.6577	8	5	6	16	5	4	5	14
92	Southwest	Navajo Power Plant	REDWALL LIMESTONE	-111.3733	36.8173	9	7	9	7	6	8	10	4
93	Southwest	Navajo Power Plant	TAPEATS SANDSTONE	-111.3733	36.8173	9	7	9	7	6	8	10	4
94	Southwest	Permian	Ellenburger	-102.4222	31.9179	167	148	89	154	117	150	132	55
95	Southwest	Permian	Leonard	-102.3314	31.9810	140	139	85	138	104	118	142	84
96	Southwest	Permian	Mississippian	-101.9963	32.5604	159	132	66	91	158	113	109	85
97	Southwest	Permian	Devonian strata	-103.4236	33.0881	74	70	12	50	77	49	38	60
98	Southwest	Denver	Lyons	-103.8946	40.0406	122	134	76	92	146	100	72	114
99	Southwest	Denver	Morrison	-103.7357	40.5110	154	104	91	92	144	115	77	112
100	Southwest	Raton	Carlile	-104.9552	37.1587	37	21	18	31	40	27	16	31
101	Southwest	Raton	Dockum	-104.8545	37.2025	26	13	13	20	23	20	0	29
102	Southwest	Raton	Forthayes	-104.9911	37.2182	37	15	23	24	36	27	15	32
103	Southwest	Raton	Glorieta	-104.7053	37.1048	34	18	23	24	35	22	15	33
104	Southwest	Raton	Codell	-104.9904	37.4119	24	19	3	40	24	12	12	32
105	Southwest	Raton	Raton	-105.0276	37.4756	5	4	2	3	4	4	2	1
106	Southwest	Raton	Graneros	-104.9423	37.1911	40	24	29	32	39	33	22	40
107	Southwest	Raton	Dakota	-104.9068	37.1778	40	19	26	34	40	32	17	43
108	Southwest	Raton	Entrada	-104.9112	37.1758	42	26	32	32	41	34	18	44

FID	PARTNER-SHIP	BASIN NAME	FORMATION	Centroid		Distance From Centroid to Edge of Formation in Given Direction [miles]							
				Longitude	Latitude	N	NE	E	SE	S	SW	W	NW
109	Southwest	Raton	Sangre De Cristo	-104.9209	37.1270	41	21	32	33	42	31	20	43
110	Southwest	Raton	Yeso	-104.6147	37.2097	13	12	23	29	15	15	21	30
111	Southwest	Raton	Greenhorn	-104.9497	37.1736	41	21	23	35	40	31	19	40
112	Southwest	Raton	Morrison	-104.9211	37.1789	43	20	28	35	42	34	20	44
113	Southwest	Raton	Pierreshale	-105.0037	37.4480	12	5	3	5	13	4	5	6
114	Southwest	Raton	Purgatoire	-104.9303	37.2169	34	19	26	31	30	27	19	36
115	Southwest	Anadarko	Chester	-102.3483	37.3775	41	22	16	31	27	30	24	6
116	Southwest	Raton	Smoky Hill Marl	-104.9401	37.3221	22	3	2	4	17	5	3	4
117	Southwest	Anadarko	Arbuckle	-102.5242	37.5575	48	26	21	40	33	46	29	26
118	Southwest	Anadarko	Atoka	-102.4314	37.6089	44	35	21	33	43	38	28	34
119	Southwest	Raton	Trinidad	-104.9690	37.3637	3	2	2	12	11	5	3	10
120	Southwest	Uinta	Dakota	-109.9604	39.7916	16	46	51	31	15	11	68	23
121	Southwest	Anadarko	Desse/Cherokee	-102.4086	37.6148	46	35	20	40	43	47	23	35
122	Southwest	Anadarko	Misener	-102.4170	37.6472	25	23	15	11	13	31	20	20
123	Southwest	Anadarko	Morrow	-102.4779	37.5818	48	45	24	46	41	51	32	23
124	Southwest	Anadarko	Simpson	-102.3252	37.6278	36	10	13	20	34	1	1	2
125	Southwest	Anadarko	Viola	-102.4778	37.7317	34	40	16	35	15	34	28	24
126	Southwest	Uinta	Entrada	-109.8025	39.7945	53	49	39	37	17	16	75	0
127	Southwest	Uinta	Frontier2	-109.5709	40.4483	5	4	4	6	5	3	5	6
128	Southwest	Uinta	Green River	-110.0550	40.2887	23	21	48	34	21	22	48	25
129	Southwest	Uinta	Frontier1	-109.2412	39.7514	37	22	13	20	23	28	10	0
130	Southwest	Uinta	Mancos	-109.8359	39.9556	43	33	44	48	29	27	59	52
131	Southwest	Uinta	Uinta1	-110.1259	40.4243	10	11	15	8	7	10	14	8
132	Southwest	Uinta	Kayenta	-110.8230	39.5575	8	10	24	7	7	9	22	9
133	Southwest	Uinta	Mesaverde	-109.8340	40.0113	37	31	42	41	30	30	46	34
134	Southwest	Uinta	Sego	-109.3916	40.4089	9	3	4	6	5	5	8	6
135	Southwest	Uinta	Uinta2	-109.4825	40.2582	5	4	6	8	4	5	7	7
136	Southwest	SanJuan	CliffHouse	-107.5372	36.6718	44	36	37	53	37	32	44	41
137	Southwest	Uinta	Wasatch	-109.9862	40.0868	30	29	49	35	37	35	65	32
138	Southwest	Uinta	White Rim/Coconino	-110.8519	39.5372	3	3	25	6	5	6	18	7
139	Southwest	SanJuan	Chinle	-108.0805	36.3269	9	10	69	5	5	71	26	62
140	Southwest	SanJuan	DeChelley	-108.4506	36.5623	33	25	49	32	36	25	35	45
141	Southwest	SanJuan	Entrada	-107.7120	36.4098	68	60	58	69	91	43	55	63
142	Southwest	SanJuan	Dakota	-107.7213	36.4886	59	60	54	63	61	57	55	60
143	Southwest	SanJuan	Elbert	-108.6438	36.7345	18	50	22	25	31	29	24	27
144	Southwest	SanJuan	Leadville	-108.1109	36.7240	40	39	43	22	26	38	51	25
145	Southwest	SanJuan	HonakerTrail	-108.3284	36.8424	38	34	38	7	8	47	29	10
146	Southwest	SanJuan	Fruitland	-107.3815	36.7212	39	21	23	45	27	18	20	45
147	Southwest	SanJuan	Lewis	-107.4356	36.7370	32	22	28	47	28	17	30	43
148	Southwest	SanJuan	Mancos	-107.7325	36.4940	45	43	44	54	34	39	54	38

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				Longitude	Latitude	N	NE	E	SE	S	SW	W	NW
149	Southwest	SanJuan	Menefee	-107.5675	36.6316	46	32	39	53	39	29	43	43
150	Southwest	SanJuan	Morrison	-107.7214	36.4563	59	59	54	64	65	61	56	64
151	Southwest	SanJuan	OrganRock	-108.7084	36.6307	25	14	14	39	15	22	19	27
152	Southwest	Green River	Morrison	-108.5172	41.4755	63	78	148	121	88	55	89	146
153	Southwest	Green River	Graneros	-107.8377	40.5769	15	12	24	28	18	14	16	33
154	Southwest	Green River	Fort Hays	-108.0562	40.8769	15	11	17	49	23	15	18	47
155	Southwest	SanJuan	Ouray	-108.2192	36.8104	27	38	48	8	5	48	47	10
156	Southwest	SanJuan	PicturedCliffs	-107.4139	36.7311	38	23	26	47	27	17	30	44
157	Southwest	SanJuan	PointLookout	-107.6287	36.5892	51	44	43	56	43	39	51	44
158	Southwest	SanJuan	Rico	-108.2824	36.8641	24	49	35	3	2	41	44	12
159	Southwest	Sierra Grande	Sangre De Cristo	-103.0843	36.3940	16	6	3	7	25	2	2	8
160	Southwest	Plateau/Coconino	Navajo	-111.6160	37.4235	8	7	8	7	7	11	15	9
161	Southwest	Plateau/Coconino	Coconino	-111.9939	37.2538	10	26	61	0	0	38	44	12
162	Southwest	Pedregosa	El Paso	-108.6051	31.7933	10	6	6	19	14	6	6	24
163	Southwest	Pedregosa	Percha	-108.3714	31.5995	4	3	2	1	4	3	1	2
164	Southwest	Pedregosa	Montoya	-108.4646	31.6016	5	4	4	7	6	3	3	8
165	Southwest	Pedregosa	Martin	-109.7933	31.5952	0	1	4	4	1	0	6	4
166	Southwest	Palo Duro	Strawn	-103.8788	34.6606	17	36	6	30	30	37	12	44
167	Southwest	Palo Duro	Clear Fork	-103.9566	34.4600	41	32	15	12	18	29	39	0
168	Southwest	Palo Duro	Cisco	-103.8888	34.7913	9	30	13	30	36	0	4	21
169	Southwest	Palo Duro	Canyon	-103.8713	34.6413	11	36	17	20	23	36	14	9
170	Southwest	Orogrande	Yeso	-107.0381	33.0811	1	11	17	13	13	11	11	17
171	Southwest	Orogrande	Montoya	-106.1454	32.8064	33	30	44	57	12	0	70	43
172	Southwest	Orogrande	Fusselman	-105.9581	32.5517	52	23	55	42	36	2	67	26
173	Southwest	Orogrande	El Paso	-106.3240	32.6820	42	44	54	64	35	40	52	62
174	Southwest	Orogrande	Bliss	-106.3478	32.6988	42	45	60	62	41	45	52	67
175	Southwest	Orogrande	Abo2	-104.9660	32.4749	5	6	5	5	4	7	4	5
176	Southwest	Orogrande	Abo1	-105.7219	33.3256	42	9	11	48	33	20	19	30
177	Southwest	Green River	Pierre	-107.8851	41.1168	12	24	17	12	11	12	18	10
178	Southwest	Green River	Green River	-107.7777	40.8040	33	35	24	37	36	27	29	33
179	Southwest	North Park	Dakota	-106.2698	40.5125	27	17	17	35	24	19	16	30
180	Southwest	SanJuan	PinkertonTrail	-108.1169	36.9413	20	26	35	40	0	29	52	20
181	Southwest	Paradox	Carmel4	-109.1723	39.3410	6	7	8	11	4	4	11	7
182	Southwest	Green River	Dakota	-108.4801	41.5094	60	74	147	124	91	54	90	143
183	Southwest	Green River	Carlile	-108.0896	41.5396	58	65	115	106	91	45	64	95
184	Southwest	Estancia	Yeso	-105.9732	35.3364	12	9	7	13	11	8	7	13
185	Southwest	Estancia	Todilto	-106.4369	35.2897	8	15	21	5	6	14	16	8
186	Southwest	Estancia	Morrison	-106.4059	35.3092	9	15	21	4	3	12	14	8
187	Southwest	Estancia	Mancos	-106.5316	35.2943	7	19	9	5	7	19	11	6
188	Southwest	Estancia	Entrada	-106.4095	35.2906	7	21	17	8	8	13	12	7

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189	Southwest	Estancia	Dakota	-106.4625	35.2937	10	18	24	3	6	24	18	10
190	Southwest	Estancia	Chinle	-106.3985	35.2729	11	27	22	12	9	19	18	9
191	Southwest	Paradox	Cutler2	-110.0932	38.6952	18	24	28	0	5	23	8	13
192	Southwest	Paradox	Carmel3	-110.9827	39.2896	11	15	9	5	9	19	10	7
193	Southwest	Paradox	Carmel2	-109.9555	39.1223	17	0	24	20	14	10	18	31
194	Southwest	Green River	Entrada	-108.4795	41.1099	76	12	74	84	63	63	80	76
195	Southwest	Paradox	Carmel1	-112.0212	37.8909	17	36	27	13	17	31	25	7
196	Southwest	Paradox	Entrada	-109.6699	39.2119	8	20	20	15	14	23	35	6
197	Southwest	Paradox	Kayenta3	-110.9528	39.2191	15	23	6	12	13	20	11	9
198	Southwest	Paradox	Cutler1	-109.1192	37.5277	40	47	20	44	35	44	29	21
199	Southwest	Paradox	Moenkopi	-109.3120	37.5515	31	24	12	26	37	19	25	16
200	Southwest	Paradox	Mancos	-109.5322	39.3174	10	14	10	5	6	20	9	9
201	Southwest	Paradox	Navajo2	-112.0128	37.7925	23	13	19	28	8	26	19	21
202	Southwest	Paradox	Kayenta1	-109.9508	39.1288	6	3	23	21	18	11	24	30
203	Southwest	Paradox	Kayenta2	-111.7507	37.9020	17	24	6	23	21	16	19	17
204	Southwest	Paradox	Kayenta4	-110.9026	38.0438	20	7	3	5	16	5	3	8
205	Southwest	Paradox	Dakota	-109.6940	39.2498	2	21	32	14	19	26	33	2
206	Southwest	Paradox	Morrison	-109.7465	39.2376	3	23	39	19	19	22	36	3
207	Southwest	Paradox	Navajo3	-110.9586	39.2524	14	21	7	9	12	20	11	8
208	Southwest	Paradox	Navajo1	-109.7349	39.1495	8	11	29	22	16	21	34	1
209	Southwest	Paradox	Navajo4	-108.4741	37.1153	4	11	12	3	4	11	12	3
210	Southwest	Piceance	Wasatch1	-108.1311	39.7752	15	10	29	16	24	15	16	27
211	Southwest	Piceance	Wasatch2	-107.7702	39.3785	8	7	1	7	6	8	3	5
212	Southwest	Piceance	Weber	-108.2301	39.8614	22	32	19	46	0	3	43	22
213	Southwest	Piceance	Rollins	-108.0040	39.4392	6	11	23	16	20	16	24	40
214	Southwest	Fort Worth Palo Duro	n/a	-98.7712	33.2708	47	55	112	99	35	33	70	146
215	Southwest	Kansas Arbuckle Miss	n/a	-99.3620	38.3884	112	136	185	124	96	164	147	157
216	Southwest	Paradox	Summerville1	-109.7706	39.1958	6	22	33	20	19	23	28	8
217	Southwest	Piceance	Mancos	-108.1393	39.5473	47	15	38	53	34	25	49	47
218	Southwest	Piceance	Maroon	-108.2542	39.8095	0	33	30	66	3	13	41	32
219	Southwest	Piceance	Mesaverde	-108.0563	39.6179	31	12	28	46	40	16	24	44
220	Southwest	Piceance	Minturn	-107.7099	39.7947	26	31	0	15	28	9	6	11
221	Southwest	Piceance	Moenkopi	-108.3307	40.0359	14	10	69	14	14	27	36	12
222	Southwest	Piceance	Morrison	-108.1312	39.5401	45	66	58	63	48	33	50	66
223	Southwest	Piceance	Mowry	-108.3448	39.8121	29	38	26	36	39	18	37	40
224	Southwest	Piceance	Parkcity	-108.7647	40.0854	1	1	7	1	1	1	4	1
225	Southwest	Piceance	Shinarump	-108.3107	39.9949	12	12	67	21	2	32	38	14
226	Southwest	Piceance	Statebridge	-108.9428	39.9366	6	14	0	0	9	9	3	3
227	Southwest	Paradox	Summerville2	-111.0146	39.2755	13	18	12	3	6	20	10	9

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228	Southwest	Piceance	Belden	-107.7896	40.1090	5	6	9	5	6	5	6	8
229	Southwest	Piceance	Corcoran	-108.0443	39.4892	40	15	35	39	34	22	35	46
230	Southwest	Piceance	Cozzette	-108.0453	39.4484	29	7	35	21	20	17	28	38
231	Southwest	South Park	Dakota	-105.7739	39.0713	2	1	3	11	4	3	5	12
232	Southwest	Piceance	Dakota	-108.1090	39.5334	46	62	60	81	48	33	51	67
233	Southwest	Piceance	Entrada	-108.3540	39.6743	38	54	27	62	36	39	36	51
234	Southwest	Piceance	Fortunion	-108.2370	39.7502	12	23	10	27	17	11	13	19
235	Southwest	Piceance	Greenriver	-108.6917	40.0729	0	0	17	3	1	0	18	0
236	Southwest	Piceance	Leadville	-108.2911	39.8891	0	29	16	9	9	14	39	0
237	Southwest	Oklahoma Basins	n/a	-98.3170	35.8658	79	114	220	147	85	79	218	114
238	Southwest	Paradox	Ouray	-109.4912	37.9331	74	43	72	68	65	63	74	97
239	PCOR	Williston Basin	Broom Creek	-101.5151	47.2023	52	43	46	50	48	50	42	54
240	PCOR	Williston Basin	Lower Cretaceous4	-106.9885	45.4701	33	26	9	19	35	28	10	23
241	PCOR	Williston Basin	Lower Cretaceous	-104.0135	46.3241	190	10	169	186	72	165	138	142
242	PCOR	Williston Basin	Lower Cretaceous5	-105.1254	44.3845	22	27	17	11	16	30	9	12
243	PCOR	Williston Basin	Lower Cretaceous3	-104.5874	43.5820	35	34	12	24	34	28	20	21
244	PCOR	Williston Basin	Lower Cretaceous6	-102.6339	48.6855	10	13	14	3	9	10	17	6
245	PCOR	Williston Basin	Lower Cretaceous2	-101.6216	47.2367	24	28	26	29	25	17	31	21
246	PCOR	Denver	Lower CretaceousD	-102.6933	41.1396	77	74	84	79	91	71	73	104
247	PCOR	Denver	Lower CretaceousD2	-101.2202	42.6773	10	7	18	10	9	2	13	12
248	PCOR	Denver	Lower CretaceousD3	-101.2092	42.3886	5	7	5	9	7	1	7	9
249	PCOR	Williston Basin	Madison	-103.6535	46.7464	149	202	200	201	138	221	193	193
250	WESTCARB	Snake River	n/a	-117.3296	43.7376	43	37	16	31	58	17	25	33
251	WESTCARB	Swauk	n/a	-120.9285	47.3499	4	5	26	16	13	13	15	29
252	WESTCARB	Methow	n/a	-120.4904	48.6386	21	11	11	37	16	6	15	33
253	WESTCARB	Hornbrook	n/a	-122.8442	42.3658	11	5	3	24	8	8	6	15
254	WESTCARB	Harney	n/a	-119.1028	43.2181	31	40	47	30	36	38	41	31
255	WESTCARB	Coos	n/a	-124.2894	42.6342	28	15	11	16	35	13	6	21
256	WESTCARB	Chiwaukum	n/a	-120.5387	47.5741	11	6	6	22	13	9	7	24
257	WESTCARB	Cuyama Basin	n/a	-119.7218	35.0316	11	6	11	31	10	10	18	31
258	WESTCARB	Sonoma Basin	n/a	-122.6974	38.3747	7	3	3	22	7	5	6	27
259	WESTCARB	La Honda Basin	n/a	-122.1992	37.2577	7	4	7	16	7	11	10	23
260	WESTCARB	Salinas Basin	n/a	-120.9685	36.0675	14	14	19	62	20	16	17	82
261	WESTCARB	Eel River Basin	n/a	-124.1219	40.5446	6	4	6	12	4	4	13	14
262	WESTCARB	Los Angeles Basin	n/a	-117.9734	33.8554	20	20	28	41	16	11	26	25
263	WESTCARB	Ventura Basin	n/a	-119.0328	34.3685	13	21	37	15	20	19	83	16
264	WESTCARB	Orinda Basin	n/a	-122.0888	37.7839	11	5	6	29	6	0	5	24
265	WESTCARB	Livermore Basin	n/a	-121.8451	37.7322	6	5	9	14	15	6	6	18
266	WESTCARB	Honey Lake Valley	n/a	-120.2834	40.2595	10	8	15	14	9	8	12	15
267	WESTCARB	California Valley	n/a	-116.0013	35.8584	7	5	5	2	4	6	3	4

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268	WESTCARB	Chicago Valley	n/a	-116.1508	35.9933	7	4	3	5	9	2	3	6
269	WESTCARB	Greenwater Valley	n/a	-116.5240	36.0854	1	0	3	17	6	3	3	17
270	WESTCARB	Alturas Valley	n/a	-120.5113	41.3788	10	11	0	4	13	5	4	6
271	WESTCARB	Death Valley	n/a	-117.0067	36.4587	20	14	14	52	25	0	14	67
272	WESTCARB	Eureka Valley	n/a	-117.7930	37.2136	8	5	3	13	7	6	5	13
273	WESTCARB	Indian Wells Valley	n/a	-117.7792	35.7154	25	18	13	13	13	27	6	12
274	WESTCARB	Amargosa Desert	n/a	-116.4337	36.2973	11	0	9	16	11	7	8	22
275	WESTCARB	Goose Lake Valley	n/a	-120.4136	41.8521	10	12	4	4	15	9	4	9
276	WESTCARB	Bristol Valley	n/a	-115.7981	34.4727	12	9	11	24	3	7	7	17
277	WESTCARB	Clipper Valley	n/a	-115.4179	34.8834	7	11	5	4	6	13	5	5
278	WESTCARB	Chuckwalla Valley	n/a	-115.1475	33.6665	4	14	20	16	12	9	32	24
279	WESTCARB	Lanfair Valley	n/a	-115.0597	35.1646	15	0	14	25	7	7	19	14
280	WESTCARB	Ivanpah Valley	n/a	-115.5458	35.1974	28	26	6	8	21	35	2	2
281	WESTCARB	Goldstone Basin	n/a	-116.9464	35.3625	8	13	18	2	8	15	14	9
282	WESTCARB	Fall River Valley	n/a	-121.4202	41.0594	5	4	6	3	4	4	6	6
283	WESTCARB	Big Valley	n/a	-121.0833	41.1517	8	4	9	3	8	7	7	5
284	WESTCARB	Fremont Valley	n/a	-118.0227	35.1766	9	25	9	8	10	22	6	4
285	WESTCARB	Mesquite Valley	n/a	-115.6677	35.7565	0	0	11	10	2	2	9	10
286	WESTCARB	Pahrump Valley	n/a	-115.9684	36.0138	0	0	14	14	4	2	4	21
287	WESTCARB	Owens Valley	n/a	-118.1416	36.7893	8	2	4	32	18	9	7	22
288	WESTCARB	Saline Valley	n/a	-117.7801	36.7502	5	4	6	19	7	6	6	15
289	WESTCARB	Searles Valley	n/a	-117.3566	35.6674	19	9	8	8	9	19	2	4
290	WESTCARB	Surprise Valley	n/a	-120.0981	41.5409	28	5	5	10	21	8	5	11
291	WESTCARB	Unnamed 12	n/a	-116.2390	35.9276	5	3	3	8	4	4	3	7
292	WESTCARB	Unnamed 5	n/a	-116.1595	34.2989	6	4	3	17	9	4	4	23
293	WESTCARB	Unnamed 6	n/a	-116.3443	34.2817	9	6	6	8	7	9	6	0
294	WESTCARB	Salton Trough	n/a	-115.6778	33.1157	23	21	43	61	36	36	41	81
295	WESTCARB	Santa Maria Basin	n/a	-120.3437	34.8897	23	12	20	37	19	20	19	42
296	WESTCARB	Ward Valley	n/a	-115.0089	34.4054	40	7	7	3	30	18	6	5
297	WESTCARB	Unnamed 3	n/a	-115.1128	34.9168	9	4	2	3	9	4	2	3
298	WESTCARB	Palen Valley	n/a	-115.2003	33.9016	8	5	6	7	9	6	6	9
299	WESTCARB	Pinto Basin	n/a	-115.6446	33.9401	5	7	14	2	3	9	18	3
300	WESTCARB	Unnamed 2	n/a	-115.1990	33.3814	5	5	19	18	10	7	6	14
301	WESTCARB	Unnamed 19	n/a	-116.2684	34.6651	6	6	2	11	5	5	4	11
302	WESTCARB	Palo Verde Valley	n/a	-114.7036	33.6324	14	9	11	11	20	16	3	24
303	WESTCARB	Unnamed 13	n/a	-115.8921	35.0535	6	2	2	5	4	3	2	6
304	WESTCARB	Shadow Valley	n/a	-115.6942	35.4608	15	4	6	12	15	4	5	8
305	WESTCARB	Unnamed 9	n/a	-116.0030	35.2838	4	5	6	9	3	3	5	9
306	WESTCARB	Pilot Knob Valley	n/a	-117.0635	35.5407	1	5	26	0	0	10	14	1
307	WESTCARB	Unnamed 10	n/a	-116.0555	35.1168	8	3	3	6	7	5	3	4

FID	PARTNER-SHIP	BASIN NAME	FORMATION	Centroid		Distance From Centroid to Edge of Formation in Given Direction [miles]							
				Longitude	Latitude	N	NE	E	SE	S	SW	W	NW
308	WESTCARB	Central Valley	n/a	-120.7163	37.5265	27	18	20	204	77	37	46	191
309	WESTCARB	Tyee Umpqua Basin	n/a	-123.6893	43.7545	77	38	41	36	62	61	26	28
310	WESTCARB	West Olympic Basin	n/a	-124.4128	47.7579	19	14	10	19	26	10	7	23
311	WESTCARB	Whatcom	n/a	-122.5257	48.8799	0	13	11	12	8	12	12	13
312	WESTCARB	Willamette Trough	n/a	-123.0267	44.9321	48	50	6	13	73	27	16	30
313	WESTCARB	n/a	n/a	-111.0024	36.1495	59	67	77	109	84	43	162	70
314	WESTCARB	Coos Bay Basin	n/a	-124.5931	43.7597	22	32	4	16	29	19	11	15
315	WESTCARB	Newport Basin	n/a	-124.2690	44.7945	19	6	6	11	11	6	7	16
316	WESTCARB	Heceta Basin	n/a	-125.1363	44.9605	53	16	15	27	52	20	13	28
317	WESTCARB	Astoria Basin	n/a	-124.3184	45.4982	24	14	8	12	22	14	10	15
318	WESTCARB	Willipa Basin	n/a	-124.7065	47.0082	37	16	12	24	40	16	12	33
319	WESTCARB	Olympic Basin	n/a	-125.4579	48.1380	10	7	22	31	16	14	23	47
320	WESTCARB	Astoria-Nehalem	n/a	-123.3781	45.9021	17	22	26	26	15	9	30	23
321	WESTCARB	Ochoco	n/a	-120.1659	44.0659	70	69	43	39	68	86	30	50
322	WESTCARB	Puget Sound	n/a	-122.4828	47.0804	89	56	33	44	103	74	26	41
323	WESTCARB	Tofino Fuca	n/a	-124.0069	48.1718	0	0	36	7	5	8	21	5
324	WESTCARB	Willapa Hills	n/a	-123.7394	46.8520	30	34	25	43	40	33	19	40

APPENDIX D: WELL ANALYSIS TO POPULATE NEEDED PARAMETERS OF NATCARB POLYGONS

The NatCarb database includes two-dimensional polygons in a geospatial database representing likely formations or structures appropriate for CO_2 sequestration. Unfortunately, aside from two-dimensional shapes and a range of potential CO_2 storage capacities, other attributes of these potential sinks are not complete. Important parameters associated with each polygon necessary for WECSsim include depth and thickness information to define the third dimension of the polygons, porosity, and permeability information. This information, along with temperature and pressure information, is necessary to estimate CO_2 behavior in the formation and water quality information necessary to evaluate the potential for water extraction, treatment, and use in conjunction with CO_2 sequestration.

D.1 Potentially Intersecting Wells

Ultimately, most of the information the analysis includes for the subsurface comes from wells, and, thus, to address the lack of information included in the NatCarb 2008 based polygons—specifically thickness, depth, water quality, and temperature—well records were utilized. A brine well database from the Kansas Geological Survey (KGS, 2006) was used. The analysis defined well records with latitude and longitude within the two-dimensional shapes of the polygons as "potentially intersecting" wells. The potentially intersecting wells associated with each polygon were found with GIS techniques. A down-selection of wells was performed for 42 of the 325 polygons that did not have depth or thickness values reported in the 2008 NatCarb database. A literature search of general USGS reports and petroleum hydrocarbon field studies and analysis of reported formation age in the well record's screened interval was compared with the age of the formation reported in the NatCarb database. This detailed analysis was used to narrow down the potentially intersecting wells to a set of wells that were likely to be associated with a given polygon. Next, the well records were further limited to cases in which the screened interval was deeper than 2,500 feet. The depth and thickness of the screened interval of all remaining wells was used to create a distribution of depths and thicknesses that is used in cases where no other depth or thickness information is available. The down selecting of potentially intersecting wells to wells likely to be associated with a given polygon was time consuming and found to be of marginal value. Thus, for all other formations with potentially intersecting wells, a depth and thickness distribution was calculated using data from all potentially intersecting wells. Some 125 of 325 (38%) polygons do not have any potentially intersecting wells with depths between 2,500 and 10,000 feet.

D.1.1 Potentially Intersecting Well-based Depth and Thickness

Potentially intersecting wells data were processed with Matlab scripts to count potentially intersecting wells for a given polygon in a given depth bin. (WECSsim uses depth bins of 500 feet (500') starting with 2,500 to 3,000 feet and ending with 9,500 to 10,000 feet for depth estimation.) WECSsim uses the top of the depth bin with the most potentially intersecting wells as the potentially intersecting well-analysis-based depth. This depth exists for any polygon with potentially intersecting wells with depths between 2,500 and 10,000 feet and may or may not be the default selected by WECSsim depending on availability of depth data from other sources or methods. The depth bins are shown in Table D-1. The average screened interval of all potentially intersecting wells associated with a given polygon is used as the potentially intersecting well-analysis-based polygon thickness.

D.1.2 Potentially Intersecting Well-based Salinity

Salinities associated with the potentially intersecting wells were binned for every 2,000 parts per million (ppm) total dissolved solids between 10,000 and 40,000 ppm, with a bin for zero to 10,000 ppm on one end and 40,000 ppm plus on the other. This count of potentially intersecting wells in given salinity bins is the only water quality information used in WECSsim, and is shown in Tables D-2 through D-4.

Table D-1. Potentially intersecting well count by depth bin for the 325 NatCarb 2008 based polygons used in WECSsim.

Note: See Table C-1 to cross reference FID to polygon name.

Number of potentially intersecting wells with depths in the following bins:																		
NatCarb FID	**< 0 ft**	**0 to 2,500 ft**	**2,500 to 3,000 ft**	**3,000 to 3,500 ft**	**3,500 to 4,000 ft**	**4,000 to 4,500 ft**	**4,500 to 5,000 ft**	**5,000 to 5,500 ft**	**5,500 to 6,000 ft**	**6,000 to 6,500 ft**	**6,500 to 7,000 ft**	**7,000 to 7,500 ft**	**7,500 to 8,000 ft**	**8,000 to 8,500 ft**	**8,500 to 9,000 ft**	**9,000 to 9,500 ft**	**9,500 to 1,0000 ft**	**> 10,000 ft**
0	0	1	1	0	0	0	0	0	2	0	0	2	0	0	1	1	1	35
1	0	390	68	72	156	181	178	267	198	207	144	209	230	294	192	127	136	1072
2	0	34	32	220	57	24	38	35	10	7	9	11	18	43	19	49	61	143
3	0	123	56	61	158	221	226	246	231	221	194	436	377	406	285	230	203	1374
4	0	43	35	228	73	47	56	99	106	132	60	40	42	73	89	77	70	519
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	2	6	6	62	80	105	3	23	29	23	58	16	21	26	9	15	44
8	0	65	125	164	3	8	1	0	0	0	0	0	0	0	0	0	0	0
9	0	334	201	183	9	17	7	2	0	0	0	0	0	0	0	0	0	0
10	0	325	201	183	9	17	7	2	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	1	0	29	2	0	4	1	4	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Number of potentially intersecting wells with depths in the following bins:																		
NatCarb FID	**< 0 ft**	**0 to 2,500 ft**	**2,500 to 3,000 ft**	**3,000 to 3,500 ft**	**3,500 to 4,000 ft**	**4,000 to 4,500 ft**	**4,500 to 5,000 ft**	**5,000 to 5,500 ft**	**5,500 to 6,000 ft**	**6,000 to 6,500 ft**	**6,500 to 7,000 ft**	**7,000 to 7,500 ft**	**7,500 to 8,000 ft**	**8,000 to 8,500 ft**	**8,500 to 9,000 ft**	**9,000 to 9,500 ft**	**9,500 to 1,0000 ft**	**> 10,000 ft**
20	0	21	7	15	42	69	70	103	132	110	121	243	336	202	239	224	227	838
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	68	32	28	69	12	1	19	0	0	1	0	1	0	0	0	0	0
23	0	333	42	21	16	11	24	61	24	13	8	37	19	18	11	1	0	2
24	0	2	0	0	1	1	3	0	0	0	2	0	4	9	3	3	1	0
25	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	3
26	0	265	141	104	81	93	70	13	25	22	12	7	1	13	0	0	0	0
27	0	191	70	44	50	83	55	13	22	22	12	7	1	13	0	0	0	0
28	0	3	1	0	6	1	1	2	3	2	1	0	1	1	0	0	0	0
29	0	0	1	1	1	4	2	11	7	1	2	0	0	4	0	0	0	0
30	0	3	1	0	4	1	0	1	0	1	0	10	9	0	5	0	1	46
31	0	34	11	20	28	22	22	12	9	13	8	13	19	4	7	1	12	71
32	0	18	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0
33	0	109	25	5	1	11	17	3	4	2	4	11	2	2	0	0	0	5
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	204	23	105	38	21	48	88	36	91	138	72	17	0	0	0	0	0
36	0	53	15	15	63	29	41	38	22	15	30	33	60	62	46	17	29	268
37	0	39	12	19	52	51	43	25	33	32	54	49	59	47	88	59	62	101
38	0	74	45	41	71	39	48	48	22	20	41	37	63	64	49	32	29	300
39	0	268	294	226	48	124	176	174	86	57	36	39	54	63	116	84	38	342
40	0	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	265	141	104	81	93	70	13	25	22	12	7	1	13	0	0	0	0
42	0	59	22	23	26	45	30	12	21	22	12	7	1	13	0	0	0	0
43	0	337	403	265	67	197	276	232	137	96	150	94	140	102	168	116	80	367
44	0	322	242	166	49	192	239	215	127	82	137	83	118	96	163	105	70	263
45	0	315	340	241	61	202	273	259	127	82	56	61	81	86	167	100	71	405
46	0	28	10	0	10	10	18	8	12	14	10	12	18	29	9	12	24	116
47	0	1	0	0	0	0	4	2	0	0	0	0	0	0	0	0	0	0
48	0	85	78	125	135	102	110	52	57	52	86	20	21	11	15	0	1	64
49	0	219	113	152	160	115	116	79	43	57	76	64	23	27	24	0	0	36
50	0	230	162	130	48	42	76	4	1	4	26	45	61	68	25	5	9	166
51	0	26	18	8	21	21	33	9	37	14	6	7	1	14	5	9	7	30
52	0	3	0	0	0	0	0	3	0	0	0	0	4	0	0	2	1	3
53	0	0	0	0	0	0	0	0	0	2	2	0	1	0	0	3	0	24

Number of potentially intersecting wells with depths in the following bins:																	
NatCarb FID	**< 0 ft**	**0 to 2,500 ft**	**2,500 to 3,000 ft**	**3,000 to 3,500 ft**	**3,500 to 4,000 ft**	**4,000 to 4,500 ft**	**4,500 to 5,000 ft**	**5,000 to 5,500 ft**	**5,500 to 6,000 ft**	**6,000 to 6,500 ft**	**6,500 to 7,000 ft**	**7,000 to 7,500 ft**	**7,500 to 8,000 ft**	**8,000 to 8,500 ft**	**8,500 to 9,000 ft**	**9,000 to 9,500 ft**	**9,500 to 1,0000 ft**	**> 10,000 ft**
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	0	128	37	82	166	103	72	123	164	171	131	86	98	62	25	7	26	58
56	0	17	2	7	6	14	50	44	161	127	172	92	107	117	230	192	96	92
57	0	17	2	7	6	14	50	44	161	127	172	92	107	117	230	192	96	92
58	0	17	2	7	6	14	50	44	161	127	172	92	107	117	230	192	96	92
59	0	16	1	1	5	12	34	37	161	127	170	89	104	104	197	185	92	92
60	0	7	1	1	5	8	25	31	159	122	157	68	81	46	51	107	81	78
61	0	1	0	0	0	1	8	4	0	31	78	16	27	20	15	60	50	44
62	0	272	156	145	135	112	130	150	88	60	90	74	121	46	21	23	10	33
63	0	19	18	21	22	36	35	11	30	51	68	47	18	10	15	8	7	19
64	0	30	8	8	23	33	53	55	103	148	149	181	142	91	58	45	52	41
65	0	79	27	32	49	68	85	87	138	174	205	232	161	98	68	50	57	53
66	0	72	36	89	51	80	130	107	133	189	179	241	176	129	83	50	60	43
67	0	251	291	239	58	195	173	162	104	70	39	46	77	71	156	96	61	327
68	0	81	18	35	123	62	66	56	54	107	124	74	77	67	109	83	77	382
69	0	2	0	0	0	0	0	3	1	5	9	21	11	10	9	14	23	81
70	0	60	1	3	0	0	0	3	0	8	2	10	3	1	5	0	2	24
71	0	265	141	104	81	93	70	13	25	22	12	7	1	13	0	0	0	0
72	0	119	21	41	134	177	81	56	33	60	27	19	19	28	55	83	149	601
73	0	285	387	248	55	197	288	252	134	98	145	92	136	95	167	97	73	380
74	0	338	412	254	66	201	287	257	136	84	132	76	105	98	170	120	80	398
75	0	244	282	196	53	188	233	173	109	83	138	83	112	89	166	93	79	297
76	0	84	30	179	398	202	98	140	110	86	85	66	44	52	74	104	167	607
77	0	105	38	101	53	80	101	113	156	197	228	269	169	119	81	55	63	67
78	0	20	4	6	6	17	14	6	11	16	28	25	2	8	9	7	4	32
79	0	18	11	17	16	17	10	2	13	18	44	22	21	22	8	4	3	2
80	0	13	5	10	5	4	22	12	21	10	108	104	52	78	56	49	56	44
81	0	23	7	7	6	18	24	16	26	18	87	62	23	17	9	13	9	41
82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Number of potentially intersecting wells with depths in the following bins:																	
NatCarb FID	< 0 ft	0 to 2,500 ft	2,500 to 3,000 ft	3,000 to 3,500 ft	3,500 to 4,000 ft	4,000 to 4,500 ft	4,500 to 5,000 ft	5,000 to 5,500 ft	5,500 to 6,000 ft	6,000 to 6,500 ft	6,500 to 7,000 ft	7,000 to 7,500 ft	7,500 to 8,000 ft	8,000 to 8,500 ft	8,500 to 9,000 ft	9,000 to 9,500 ft	9,500 to 1,0000 ft	> 10,000 ft
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
94	0	341	414	253	66	202	296	256	139	95	142	90	135	99	170	121	80	406
95	0	342	409	252	65	201	294	254	137	85	64	84	129	100	170	121	80	398
96	0	339	385	246	56	197	283	240	134	97	145	91	137	100	168	117	79	376
97	0	33	15	163	363	173	101	117	83	47	56	63	53	49	63	63	144	473
98	0	7	1	9	15	83	229	117	69	110	83	36	15	19	56	93	2	1
99	0	7	5	14	25	91	234	124	75	109	81	36	16	19	56	93	2	1
100	0	6	1	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0
101	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
102	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
103	0	6	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
104	0	1	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
105	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
106	0	6	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0
107	0	5	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0
108	0	6	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0
109	0	4	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0
110	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
111	0	6	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0
112	0	6	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0
113	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
114	0	3	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
115	0	1	0	2	1	2	2	0	2	1	0	0	0	0	0	0	0	0
116	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
117	0	1	0	4	1	3	2	2	2	1	0	0	0	0	0	0	0	0
118	0	2	0	4	1	3	4	2	3	1	0	0	0	0	0	0	0	0
119	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120	0	13	11	8	12	30	19	33	50	11	2	2	2	0	3	3	3	1
121	0	2	0	4	1	2	4	2	3	1	0	0	0	0	0	0	0	0

Number of potentially intersecting wells with depths in the following bins:																		
NatCarb FID	**< 0 ft**	**0 to 2,500 ft**	**2,500 to 3,000 ft**	**3,000 to 3,500 ft**	**3,500 to 4,000 ft**	**4,000 to 4,500 ft**	**4,500 to 5,000 ft**	**5,000 to 5,500 ft**	**5,500 to 6,000 ft**	**6,000 to 6,500 ft**	**6,500 to 7,000 ft**	**7,000 to 7,500 ft**	**7,500 to 8,000 ft**	**8,000 to 8,500 ft**	**8,500 to 9,000 ft**	**9,000 to 9,500 ft**	**9,500 to 1,0000 ft**	**> 10,000 ft**
122	0	0	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0
123	0	2	0	4	1	3	4	2	4	1	0	0	0	0	0	0	0	0
124	0	0	0	3	1	2	0	0	3	0	0	0	0	0	0	0	0	0
125	0	0	0	4	1	2	1	1	2	0	0	0	0	0	0	0	0	0
126	0	7	1	6	8	17	19	39	12	3	1	2	1	0	2	3	3	1
127	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
128	0	4	10	5	7	21	30	55	105	18	12	5	9	6	5	17	5	82
129	0	2	3	5	6	11	12	33	5	1	0	3	2	0	1	4	2	0
130	0	4	13	11	22	44	36	47	101	24	4	1	2	0	6	17	4	66
131	0	0	1	0	0	0	0	1	0	0	0	0	2	1	2	16	3	62
132	0	2	0	1	2	1	2	0	1	0	1	1	2	0	1	0	1	1
133	0	4	13	11	25	49	43	64	111	26	12	6	12	1	6	15	3	57
134	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0
135	0	0	3	3	5	5	2	8	35	12	6	2	4	0	0	0	0	0
136	0	143	18	22	27	20	11	21	66	113	81	23	20	10	3	0	0	4
137	0	16	13	11	24	51	50	74	114	24	14	7	14	6	8	19	7	80
138	0	5	0	1	2	0	2	0	1	0	1	1	2	0	1	0	1	1
139	0	126	3	13	20	10	22	36	35	49	29	4	10	1	8	2	0	0
140	0	116	3	7	2	6	15	37	20	92	44	9	3	0	8	2	0	2
141	0	308	26	32	32	35	109	68	78	140	83	29	22	11	11	5	2	4
142	0	303	24	31	32	34	109	68	78	140	83	23	21	11	11	5	2	4
143	0	29	3	7	2	4	8	2	13	56	28	6	3	0	8	5	2	2
144	0	198	8	15	18	11	25	42	41	137	55	17	12	8	1	3	2	2
145	0	38	4	8	0	7	15	4	14	36	32	11	2	0	8	5	2	2
146	0	21	2	15	20	11	1	1	13	6	2	2	15	9	2	0	0	1
147	0	31	8	15	20	12	4	3	13	6	6	12	18	10	2	0	0	1
148	0	287	17	23	30	34	106	67	78	139	75	20	16	9	3	0	0	2
149	0	258	18	22	28	20	22	55	71	134	77	23	19	10	6	0	0	3
150	0	304	25	31	32	35	109	68	78	140	83	23	21	11	11	5	2	4
151	0	12	0	0	1	1	0	0	0	39	12	6	2	0	0	0	0	0
152	0	539	378	542	521	355	425	282	314	375	349	274	239	182	257	234	308	826
153	0	17	0	22	31	11	16	10	16	14	6	11	9	4	8	6	2	4
154	0	64	30	100	78	101	78	62	29	39	36	23	14	22	30	2	0	48
155	0	78	9	13	6	10	16	5	21	68	44	14	12	7	9	5	2	2

Number of potentially intersecting wells with depths in the following bins:																		
NatCarb FID	**< 0 ft**	**0 to 2,500 ft**	**2,500 to 3,000 ft**	**3,000 to 3,500 ft**	**3,500 to 4,000 ft**	**4,000 to 4,500 ft**	**4,500 to 5,000 ft**	**5,000 to 5,500 ft**	**5,500 to 6,000 ft**	**6,000 to 6,500 ft**	**6,500 to 7,000 ft**	**7,000 to 7,500 ft**	**7,500 to 8,000 ft**	**8,000 to 8,500 ft**	**8,500 to 9,000 ft**	**9,000 to 9,500 ft**	**9,500 to 1,0000 ft**	**> 10,000 ft**
156	0	27	7	15	20	12	3	3	13	6	2	10	18	10	2	0	0	1
157	0	293	20	23	30	34	108	68	78	135	82	23	20	10	3	0	0	4
158	0	32	7	7	3	8	8	4	6	42	35	14	3	0	9	5	2	0
159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
160	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
161	0	8	0	0	0	0	1	2	1	1	0	0	1	1	1	0	0	0
162	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
163	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
164	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
165	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
166	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
167	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
168	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
169	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
171	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
172	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
173	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
174	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
175	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
176	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
177	0	133	62	118	87	81	77	33	13	22	15	7	8	23	22	0	12	12
178	0	171	77	161	154	107	100	46	31	52	42	24	38	51	35	6	2	27
179	0	8	0	0	1	1	8	7	12	6	1	0	0	0	0	1	0	0
180	0	28	3	10	1	1	2	0	4	14	10	5	9	7	8	5	2	0
181	0	0	3	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
182	0	505	355	489	506	359	423	262	306	356	347	242	235	168	240	233	307	840
183	0	407	235	356	397	313	363	261	293	359	314	200	190	141	216	208	271	576
184	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
185	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
186	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
187	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
189	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Number of potentially intersecting wells with depths in the following bins:																		
NatCarb FID	**< 0 ft**	**0 to 2,500 ft**	**2,500 to 3,000 ft**	**3,000 to 3,500 ft**	**3,500 to 4,000 ft**	**4,000 to 4,500 ft**	**4,500 to 5,000 ft**	**5,000 to 5,500 ft**	**5,500 to 6,000 ft**	**6,000 to 6,500 ft**	**6,500 to 7,000 ft**	**7,000 to 7,500 ft**	**7,500 to 8,000 ft**	**8,000 to 8,500 ft**	**8,500 to 9,000 ft**	**9,000 to 9,500 ft**	**9,500 to 1,0000 ft**	**> 10,000 ft**
190	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
191	0	3	4	1	0	2	0	1	1	1	3	0	2	4	12	1	0	0
192	0	0	0	0	1	0	0	0	0	0	0	9	0	0	0	1	0	0
193	0	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
194	0	368	222	353	350	265	277	179	169	194	221	119	86	85	75	34	10	235
195	0	21	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
196	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
197	0	1	0	0	1	0	0	0	0	0	0	9	0	3	1	1	0	0
198	0	8	0	0	2	0	4	22	77	14	4	2	2	1	0	0	0	1
199	0	2	0	0	0	1	2	8	43	15	2	2	2	1	0	0	0	0
200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
201	0	9	0	0	1	0	0	0	0	3	9	5	1	1	7	0	0	1
202	0	4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
203	0	0	0	0	1	0	0	0	0	3	8	4	0	0	7	0	0	0
204	0	0	0	0	0	0	2	1	0	1	0	3	1	1	0	0	0	0
205	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1
206	0	0	1	0	1	0	0	1	0	0	0	0	0	0	1	1	0	1
207	0	1	0	0	1	0	0	0	0	0	0	9	0	0	0	1	0	0
208	0	5	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1
209	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
210	0	2	6	9	9	1	1	1	9	3	0	4	0	0	0	0	0	0
211	0	0	1	0	1	0	0	0	0	0	2	0	0	0	2	0	0	0
212	0	19	20	25	24	22	15	8	48	43	53	17	5	1	0	1	2	5
213	0	0	5	1	1	3	2	4	7	2	2	4	0	0	2	0	0	0
214	0	7	6	6	12	16	10	6	8	14	1	3	1	1	4	0	0	0
215	0	455	231	592	404	348	169	36	26	2	11	1	0	0	0	0	0	0
216	0	3	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
217	0	9	11	9	4	10	7	11	28	8	4	12	1	0	4	2	2	5
218	0	9	12	10	15	6	11	2	12	19	28	14	5	0	2	2	0	4
219	0	7	11	9	10	5	4	11	22	6	4	8	0	0	2	0	2	3
220	0	1	0	0	1	2	3	0	1	12	27	10	0	0	0	0	0	4
221	0	19	14	16	19	24	13	5	26	40	50	14	5	1	0	1	0	5
222	0	23	25	31	30	26	20	12	50	49	53	21	5	1	6	2	0	7
223	0	18	21	27	27	20	13	14	45	46	53	21	5	1	4	2	0	5

Number of potentially intersecting wells with depths in the following bins:																		
NatCarb FID	< 0 ft	0 to 2,500 ft	2,500 to 3,000 ft	3,000 to 3,500 ft	3,500 to 4,000 ft	4,000 to 4,500 ft	4,500 to 5,000 ft	5,000 to 5,500 ft	5,500 to 6,000 ft	6,000 to 6,500 ft	6,500 to 7,000 ft	7,000 to 7,500 ft	7,500 to 8,000 ft	8,000 to 8,500 ft	8,500 to 9,000 ft	9,000 to 9,500 ft	9,500 to 1,0000 ft	> 10,000 ft
224	0	0	1	7	2	5	2	1	8	5	3	0	0	1	0	0	0	0
225	0	20	19	25	27	19	13	7	27	39	50	16	5	1	0	1	0	5
226	0	0	2	2	0	0	0	0	0	1	0	2	1	0	0	1	0	0
227	0	3	0	0	5	0	0	0	0	0	0	9	0	0	0	1	0	0
228	0	0	0	2	1	0	0	2	0	12	20	9	0	0	0	0	0	0
229	0	6	10	9	10	9	7	8	20	5	2	5	0	0	2	0	2	2
230	0	0	3	1	1	5	7	3	5	3	2	4	0	0	2	0	2	2
231	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
232	0	23	25	30	30	26	20	13	50	48	53	21	5	1	4	2	2	7
233	0	25	24	31	30	29	20	9	47	48	53	20	5	1	4	2	0	7
234	0	5	5	3	3	5	1	5	11	3	0	4	0	0	0	0	0	0
235	0	2	2	4	1	0	0	0	1	3	0	0	0	0	0	0	0	0
236	0	4	10	13	11	7	6	9	22	18	18	12	1	0	2	2	0	2
237	0	1063	816	540	429	733	416	283	193	358	236	225	131	94	76	61	69	244
238	0	19	5	11	15	11	19	43	100	28	13	8	7	8	20	2	0	9
239	0	0	0	0	0	0	2	0	1	1	6	0	3	5	5	0	0	4
240	0	8	2	0	0	0	3	0	3	0	2	2	0	0	0	0	0	0
241	0	26	15	16	17	39	114	96	184	135	161	139	108	118	217	219	93	86
242	0	9	2	0	3	3	14	24	42	71	38	56	73	37	35	14	22	5
243	0	14	11	16	16	14	7	8	7	3	12	8	10	0	2	0	0	0
244	0	0	0	0	0	0	0	0	0	7	20	13	35	8	0	0	0	0
245	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0
246	0	2	5	9	18	73	198	91	42	62	51	6	0	0	0	0	0	0
247	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
248	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
249	0	95	34	108	92	132	205	171	312	268	362	320	326	298	351	322	144	193
250	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
251	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
252	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
253	0	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
254	0	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
255	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
256	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
257	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Number of potentially intersecting wells with depths in the following bins:																		
NatCarb FID	< 0 ft	0 to 2,500 ft	2,500 to 3,000 ft	3,000 to 3,500 ft	3,500 to 4,000 ft	4,000 to 4,500 ft	4,500 to 5,000 ft	5,000 to 5,500 ft	5,500 to 6,000 ft	6,000 to 6,500 ft	6,500 to 7,000 ft	7,000 to 7,500 ft	7,500 to 8,000 ft	8,000 to 8,500 ft	8,500 to 9,000 ft	9,000 to 9,500 ft	9,500 to 1,0000 ft	> 10,000 ft
258	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
259	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
260	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
261	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
262	0	3	2	18	14	6	2	4	3	2	1	2	0	0	1	1	0	2
263	0	0	0	0	0	0	1	0	0	0	2	9	5	2	1	4	0	6
264	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
265	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
266	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
267	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
268	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
269	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
270	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
271	0	178	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
272	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
273	0	1204	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
274	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
275	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
276	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
277	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
278	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
279	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
280	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
281	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
282	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
283	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
284	0	445	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
285	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
286	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
287	0	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
288	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
289	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
290	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
291	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Number of potentially intersecting wells with depths in the following bins:

NatCarb FID	< 0 ft	0 to 2,500 ft	2,500 to 3,000 ft	3,000 to 3,500 ft	3,500 to 4,000 ft	4,000 to 4,500 ft	4,500 to 5,000 ft	5,000 to 5,500 ft	5,500 to 6,000 ft	6,000 to 6,500 ft	6,500 to 7,000 ft	7,000 to 7,500 ft	7,500 to 8,000 ft	8,000 to 8,500 ft	8,500 to 9,000 ft	9,000 to 9,500 ft	9,500 to 1,0000 ft	> 10,000 ft
292	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
293	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
294	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
295	0	0	1	0	2	1	0	2	2	1	0	0	0	0	0	0	0	0
296	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
297	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
298	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
299	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
301	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
303	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
304	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
305	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
306	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
307	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
308	0	55	12	6	6	6	7	5	18	11	12	3	4	2	3	2	0	10
309	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
310	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
311	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
312	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
313	0	42	0	0	2	1	10	11	10	8	0	2	0	0	0	0	0	0
314	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
315	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
316	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
317	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
318	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
319	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
321	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
322	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
323	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
324	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table D-2. Potentially intersecting well count by salinity bin (in parts per thousand total dissolved solids) for wells between 2,500 and 5,000 feet deep for the 325 NatCarb 2008 based polygons used in WECSsim.

Note: See Table C-1 to cross reference FID to polygon name. Table indicates the number of wells with depth between 2,500 and 5,000 feet in the following salinity bins.

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
1	74	10	14	17	35	26	45	27	23	22	11	20	26	18	22	15	250
2	4	4	0	2	0	0	0	1	0	2	2	0	1	0	2	8	345
3	54	6	12	16	37	26	40	26	21	22	13	19	26	20	21	13	350
4	4	4	0	2	0	0	0	2	0	3	2	0	2	0	3	8	409
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	6	5	69	62	6	4	1	1	3	5	2	2	4	5	0	1	83
8	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	299
9	2	0	2	1	0	0	0	1	3	3	0	1	0	0	1	1	402
10	2	0	2	1	0	0	0	1	3	3	0	1	0	0	1	1	402
11	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	2	0	0	0	0	2	0	1	0	0	0	0	1	0	0	1	196
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	141
23	5	0	2	1	0	1	1	1	0	0	0	0	0	0	0	2	89
24	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
25	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	357	27	24	16	20	15	16	2	2	1	1	0	1	0	0	0	7
27	202	13	12	13	19	15	16	2	2	1	1	0	1	0	0	0	5
28	8	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	8	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
30	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	89	3	0	2	1	0	1	2	1	1	0	0	0	1	0	0	2
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
33	58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	174	24	4	2	1	2	4	4	6	4	0	0	3	0	0	6	1
36	133	11	6	5	4	2	0	0	0	0	0	0	0	0	0	0	2
37	162	2	0	0	2	2	0	0	0	0	0	0	0	0	0	2	4
38	214	11	6	5	4	2	0	0	0	0	0	0	0	0	0	0	2
39	57	13	14	7	7	10	12	8	10	8	10	12	12	9	5	8	665
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
41	357	27	24	16	20	15	16	2	2	1	1	0	1	0	0	0	7
42	60	13	11	12	17	14	13	2	2	1	0	0	1	0	0	0	0
43	57	16	16	9	9	14	15	9	11	11	13	15	16	12	5	11	966
44	24	6	10	9	7	7	9	6	8	9	7	9	9	9	3	10	744
45	60	14	16	10	9	11	14	9	12	10	13	16	14	12	5	11	880
46	3	0	3	12	14	6	2	4	0	0	2	2	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0
48	123	51	21	25	26	21	36	28	30	27	25	18	10	13	10	4	80
49	283	39	48	32	14	32	13	26	29	23	15	21	12	5	4	8	50
50	408	27	16	0	3	0	0	3	0	0	0	0	0	0	0	0	0
51	75	13	11	0	0	0	0	0	0	0	0	0	0	0	0	0	2
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	347	29	16	7	3	4	11	3	4	2	12	0	1	0	0	3	12
56	55	6	4	4	0	0	1	0	0	1	1	0	0	0	1	0	6
57	55	6	4	4	0	0	1	0	0	1	1	0	0	0	1	0	6
58	55	6	4	4	0	0	1	0	0	1	1	0	0	0	1	0	6
59	36	4	3	3	0	0	1	0	0	0	0	0	0	0	1	0	5
60	24	4	3	2	0	0	1	0	0	0	0	0	0	0	1	0	5
61	2	2	2	1	0	0	0	0	0	0	0	0	0	0	1	0	1
62	466	88	47	12	33	15	5	3	2	1	3	0	0	0	0	0	2
63	96	14	9	8	2	2	0	0	0	0	0	0	0	0	0	0	1
64	118	3	2	0	1	0	0	0	0	0	0	0	0	0	0	0	1
65	210	19	13	10	4	4	0	0	0	0	0	0	0	0	0	0	1
66	285	23	19	14	30	13	1	0	0	0	0	0	0	0	0	0	1
67	60	14	17	8	8	11	13	9	11	8	13	16	13	9	5	10	730
68	275	10	0	2	2	2	0	0	0	0	0	0	0	0	0	4	6
69	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
71	357	27	24	16	20	15	16	2	2	1	1	0	1	0	0	0	7
72	35	21	26	11	16	16	8	4	10	9	8	6	6	7	4	1	254
73	57	14	16	9	7	11	13	9	11	10	12	14	13	12	4	11	949
74	58	15	16	10	8	11	14	9	11	10	13	16	14	12	5	11	984
75	23	12	7	9	5	10	10	6	11	6	9	11	13	10	2	10	795
76	123	58	46	33	36	25	19	14	17	14	10	12	10	13	7	6	451
77	298	23	24	11	11	5	0	0	0	0	0	0	0	0	0	0	1
78	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
79	36	14	9	8	1	2	0	0	0	0	0	0	0	0	0	0	1
80	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
81	62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
94	60	15	16	10	8	11	14	9	11	10	13	16	14	12	5	11	993
95	57	15	16	10	8	11	14	9	11	10	13	16	14	12	5	11	986
96	54	15	16	10	8	11	13	9	11	10	13	13	13	12	4	10	942
97	114	46	39	29	27	21	17	10	19	13	9	10	9	11	8	6	410
98	141	8	13	17	16	12	4	10	8	9	6	6	3	4	5	4	71
99	166	10	13	17	16	12	4	10	9	9	6	7	3	4	5	4	74
100	2	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
101	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
102	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
103	2	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
104	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
105	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
106	3	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
107	3	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
108	3	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
109	3	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
110	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
111	3	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
112	3	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
113	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
114	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
115	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	5
116	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
117	0	0	1	1	1	0	0	0	1	0	0	0	0	1	0	0	5
118	0	0	1	1	1	0	0	0	1	0	0	0	0	1	1	0	6
119	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120	44	5	3	2	1	0	2	0	0	3	0	2	2	2	0	1	13
121	0	0	1	1	1	0	0	0	1	0	0	0	0	1	1	0	5
122	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
123	0	0	1	1	1	0	0	0	1	0	0	0	0	1	1	0	6
124	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	4
125	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	5
126	40	1	2	3	0	0	1	0	0	0	0	0	1	0	0	1	2
127	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
128	47	8	2	2	3	1	1	0	2	1	0	0	1	0	0	1	4
129	32	1	1	1	0	0	1	0	0	0	0	0	1	0	0	0	0
130	58	9	3	3	6	1	3	0	2	6	1	3	4	2	1	0	24
131	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
132	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
133	68	9	4	4	6	2	3	0	2	7	1	3	4	2	1	1	24
134	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
135	7	2	1	2	1	1	1	0	0	0	0	0	0	0	0	1	2
136	20	4	2	9	1	3	0	2	3	2	1	1	2	1	0	2	7
137	78	9	4	3	6	2	2	0	3	7	1	3	3	2	1	1	24
138	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
139	8	1	4	2	0	4	0	5	1	3	1	2	0	1	0	1	13
140	5	0	2	1	0	2	0	4	0	0	1	1	0	0	0	0	13
141	41	9	6	10	2	7	1	7	3	3	2	2	4	2	2	2	28
142	39	9	6	10	2	6	1	7	3	3	2	2	4	2	2	2	27
143	3	1	2	1	0	1	0	4	0	0	0	1	0	0	0	0	8
144	16	3	2	5	0	2	0	1	1	0	2	0	2	1	0	2	17
145	9	2	1	4	0	1	0	4	0	0	1	1	0	0	0	0	7
146	10	2	2	2	1	1	0	2	1	0	0	0	1	1	0	1	0

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
147	13	3	2	4	1	1	0	2	2	0	0	0	1	1	0	1	0
148	34	8	6	7	2	6	0	3	2	3	2	1	4	2	2	2	24
149	24	5	3	8	1	3	0	2	3	2	1	1	2	1	0	2	12
150	40	9	6	10	2	6	1	7	3	3	2	2	4	2	2	2	28
151	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
152	1206	152	106	69	47	65	67	60	63	52	61	42	23	18	16	15	149
153	67	4	4	2	0	3	0	0	0	0	0	0	0	0	0	0	0
154	131	29	35	32	8	11	6	17	10	12	12	21	9	4	4	5	38
155	11	3	2	5	0	2	0	5	1	0	1	1	1	0	0	1	14
156	12	3	2	4	1	1	0	2	2	0	0	0	1	1	0	1	0
157	35	8	5	10	2	6	0	3	3	3	2	1	4	2	2	2	25
158	7	3	1	4	0	1	0	4	0	0	1	1	0	0	0	0	7
159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
161	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
162	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
163	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
164	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
165	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
166	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
167	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
168	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
169	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
171	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
172	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
173	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
174	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
175	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
176	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
177	192	27	29	23	8	14	5	21	12	8	11	18	11	3	4	5	32
178	322	38	35	30	8	20	10	21	14	10	12	20	12	3	4	5	29
179	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180	2	1	0	0	0	1	0	5	0	0	0	1	0	0	0	0	4
181	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	3
182	1137	140	102	69	47	65	67	57	63	52	60	42	23	18	16	15	149
183	744	140	83	69	42	58	56	54	49	49	58	42	23	18	16	15	138
184	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
185	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
186	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
187	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
189	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
190	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
191	1	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0	2
192	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
193	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
194	599	103	71	62	44	63	60	54	60	52	40	39	23	18	16	12	143
195	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
196	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
197	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
198	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	4
199	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
201	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
202	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
203	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
204	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
205	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
206	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
207	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
208	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
209	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
210	17	3	0	2	0	1	2	0	1	0	0	0	0	0	0	0	0
211	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
212	55	8	5	6	11	1	3	1	3	2	1	0	0	2	1	1	6
213	4	0	0	0	1	1	3	0	2	0	0	0	0	0	0	0	1
214	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	48
215	8	7	3	2	14	49	55	37	34	26	25	27	36	26	35	30	1234
216	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
217	20	4	1	3	3	1	4	1	3	0	0	0	0	0	0	0	1
218	29	3	1	5	3	1	0	1	2	2	1	0	0	0	1	0	5
219	22	3	0	2	3	1	3	1	3	0	0	0	0	0	0	0	1
220	0	0	1	1	2	0	0	1	1	0	0	0	0	0	0	0	0
221	52	5	4	3	8	0	1	1	1	2	1	0	0	2	1	1	4
222	67	8	5	6	11	2	4	2	4	2	2	0	1	2	1	1	14

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
223	61	8	4	5	8	1	3	1	3	2	2	0	0	2	1	1	6
224	12	1	0	0	1	0	0	1	0	0	0	0	0	1	0	1	0
225	64	6	4	5	8	1	1	1	2	2	1	0	0	2	1	1	4
226	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
227	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
228	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0
229	24	3	1	3	3	2	4	1	3	0	0	0	0	0	0	0	1
230	4	0	1	1	3	1	3	1	2	0	0	0	0	0	0	0	1
231	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
232	67	8	5	6	11	2	4	2	4	2	2	0	1	2	1	1	13
233	70	8	5	6	11	1	3	2	4	2	1	0	1	2	1	1	16
234	10	0	0	2	0	0	3	0	2	0	0	0	0	0	0	0	0
235	4	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0
236	24	5	0	3	1	1	3	0	3	1	1	0	0	0	1	0	4
237	35	6	20	4	6	6	2	13	8	10	7	7	12	4	10	14	2770
238	8	2	0	1	1	0	2	3	1	1	1	0	1	1	0	0	39
239	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
240	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
241	154	9	9	8	6	3	1	2	1	1	0	0	0	0	1	0	6
242	20	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
243	30	14	9	8	1	2	0	0	0	0	0	0	0	0	0	0	0
244	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
245	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
246	117	11	9	11	13	9	4	8	8	9	6	7	2	4	5	5	75
247	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
248	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
249	257	17	14	14	8	4	6	3	3	1	3	1	0	1	1	0	238
250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
251	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
252	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
253	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
254	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
255	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
256	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
257	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
258	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
259	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
260	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
261	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
262	0	0	0	1	0	0	2	0	1	4	4	14	9	2	0	1	4
263	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
264	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
265	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
266	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
267	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
268	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
269	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
270	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
271	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
272	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
273	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
274	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
275	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
276	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
277	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
278	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
279	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
280	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
281	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
282	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
283	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
284	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
285	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
286	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
287	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
288	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
289	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
290	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
291	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
292	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
293	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
294	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
295	1	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0
296	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
297	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
298	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
299	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
301	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
303	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
304	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
305	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
306	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
307	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
308	2	2	0	2	6	4	0	4	2	2	3	1	3	1	2	1	1
309	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
310	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
311	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
312	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
313	1	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1	8
314	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
315	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
316	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
317	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
318	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
319	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
321	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
322	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
323	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
324	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table D-3. Potentially intersecting well count by salinity bin (in parts per thousand total dissolved solids) for wells between 5,000 and 7,500 feet deep for the 325 NatCarb 2008 based polygons used in WECSsim.

Note: See Table C-1 to cross reference FID to polygon name. Table indicates the number of wells with depth between 5,000 and 7,500 feet in the following salinity bins.

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
1	36	21	28	14	11	27	14	15	19	10	10	10	10	8	12	2	778
2	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	69
3	56	24	36	18	32	46	54	43	47	25	20	21	28	20	15	8	835
4	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	434
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	6	3	0	2	1	3	2	0	3	1	1	4	1	0	0	1	108
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
11	0	1	0	0	0	3	2	1	0	1	2	2	2	1	3	0	18
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	6	3	3	2	8	15	33	26	20	5	2	4	4	3	3	4	568
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20
23	1	0	0	0	0	0	0	0	0	0	2	1	0	0	3	0	125
24	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
25	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	49	7	3	3	6	2	2	2	1	1	0	2	0	0	0	0	1
27	47	6	3	3	6	2	2	2	1	1	0	2	0	0	0	0	1
28	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	8	0	0	1	0	1	0	0	1	1	0	0	0	0	0	0	0
31	31	4	2	3	2	1	2	1	4	2	0	1	0	0	0	0	2

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	21	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	228	29	31	20	13	7	27	6	8	6	14	10	0	2	12	6	6
36	105	12	4	4	7	6	0	0	0	0	0	0	0	0	0	0	0
37	140	12	11	4	1	1	2	0	1	2	0	2	0	1	0	1	4
38	137	10	4	4	7	6	0	0	0	0	0	0	0	0	0	0	0
39	2	6	0	1	0	2	0	5	4	2	2	3	5	9	5	5	341
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	49	7	3	3	6	2	2	2	1	1	0	2	0	0	0	0	1
42	46	5	3	3	6	2	2	2	1	1	0	2	0	0	0	0	1
43	10	7	0	3	1	2	1	5	6	3	2	10	10	10	5	9	625
44	6	6	0	2	1	2	1	5	6	3	2	10	10	10	5	9	566
45	5	6	0	2	2	2	1	5	6	3	2	10	10	10	6	6	509
46	17	7	12	0	0	3	4	2	2	2	2	0	2	0	0	0	3
47	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
48	95	22	15	9	11	10	2	9	6	2	0	5	4	9	6	6	56
49	91	42	16	17	25	18	21	19	5	1	6	8	12	2	5	3	28
50	52	4	9	0	0	1	0	3	0	4	0	0	3	1	0	0	3
51	62	3	3	2	1	1	0	0	0	0	0	0	0	0	0	0	0
52	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	1
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	338	91	67	70	29	0	20	10	11	6	9	1	7	6	3	5	2
56	54	5	11	11	3	10	4	2	6	5	7	5	4	5	6	6	452
57	54	5	11	11	3	10	4	2	6	5	7	5	4	5	6	6	452
58	54	5	11	11	3	10	4	2	6	5	7	5	4	5	6	6	452
59	48	3	11	11	3	10	4	2	6	5	7	5	4	4	6	6	449
60	32	0	11	10	2	9	4	2	5	5	6	5	4	4	6	5	427
61	1	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	125
62	314	31	24	23	21	27	15	2	2	0	0	0	0	0	0	0	2
63	124	14	9	17	15	5	6	1	3	1	0	2	1	1	0	0	8
64	350	44	47	64	27	20	23	11	0	1	5	7	3	3	3	1	26
65	479	59	55	77	42	27	28	11	3	2	5	7	3	4	3	1	29
66	519	60	55	54	35	33	26	10	3	2	5	7	3	4	3	1	29
67	3	5	0	0	0	1	0	3	4	2	2	7	4	9	1	5	375
68	284	24	24	12	5	1	14	4	5	2	5	9	0	1	6	2	6
69	23	7	8	0	0	1	0	0	0	0	0	0	0	0	0	0	0

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
70	0	0	0	5	4	1	0	0	0	0	4	4	0	0	0	0	5
71	49	7	3	3	6	2	2	2	1	1	0	2	0	0	0	0	1
72	2	2	3	3	6	4	1	5	5	0	6	8	6	6	2	1	134
73	7	7	0	2	1	2	1	3	6	3	2	10	10	10	5	8	644
74	7	7	0	2	1	2	1	5	6	3	2	10	10	10	5	9	605
75	7	7	0	2	1	2	0	4	4	2	2	9	7	10	5	8	516
76	7	1	4	4	9	6	4	5	6	4	7	10	6	10	3	3	385
77	565	69	68	81	48	35	28	11	3	2	5	7	3	4	3	1	29
78	29	9	5	16	15	2	4	0	3	0	0	0	0	1	0	0	2
79	86	2	3	0	0	3	0	0	0	1	0	0	0	0	0	0	4
80	91	19	27	49	24	13	15	5	0	1	0	5	1	1	1	0	2
81	73	19	17	49	29	8	6	1	3	0	0	0	0	1	0	0	2
82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
94	7	7	0	2	1	2	1	5	6	3	2	10	10	10	5	9	642
95	8	6	0	2	1	2	1	5	6	3	2	10	10	10	5	8	545
96	7	7	0	2	1	2	1	5	6	3	2	10	10	10	5	9	627
97	6	2	3	5	6	5	3	3	3	2	2	2	1	4	1	2	297
98	272	34	30	21	20	13	8	5	0	1	1	0	0	0	1	0	9
99	270	34	30	23	20	13	9	7	0	2	1	0	0	0	1	0	15
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
101	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
102	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
103	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
105	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
107	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
111	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
112	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
113	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
114	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
115	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
116	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
117	1	0	0	0	1	0	2	0	0	0	0	0	0	0	0	0	1
118	1	0	0	0	1	0	2	0	0	0	0	0	0	0	0	0	2
119	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120	45	5	8	4	9	4	0	4	1	1	2	0	1	1	2	1	8
121	1	0	0	0	1	0	2	0	0	0	0	0	0	0	0	0	2
122	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
123	1	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	2
124	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2
125	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1
126	49	0	0	1	1	0	0	0	1	0	0	0	0	1	0	0	4
127	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
128	92	5	7	6	13	6	6	6	3	5	9	3	2	1	7	4	20
129	39	0	0	0	2	0	0	0	1	0	0	0	0	0	0	0	0
130	58	5	11	7	10	5	6	6	3	5	8	4	2	3	8	5	31
131	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
132	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
133	91	5	11	7	12	8	6	7	3	5	9	4	2	3	8	5	33
134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
135	20	1	2	5	4	3	2	2	2	4	6	3	1	0	2	3	3
136	53	6	10	15	8	13	6	9	5	5	6	7	1	6	3	3	30
137	105	5	11	7	12	8	6	8	3	5	9	4	2	3	8	5	32
138	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
139	7	2	2	4	1	4	3	3	1	1	2	1	2	1	0	0	48
140	13	4	2	6	5	10	3	5	1	4	6	4	2	2	1	2	77
141	58	7	11	16	10	15	7	9	6	6	8	9	2	8	3	4	51
142	58	7	11	16	10	15	7	9	6	6	8	9	2	8	3	4	45
143	2	0	0	1	0	0	0	0	1	0	1	0	1	4	1	1	70
144	37	5	7	8	6	12	3	7	4	4	6	4	1	6	3	3	93
145	6	0	2	2	0	0	0	3	4	0	0	0	0	4	1	2	43

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
146	6	2	3	1	0	0	1	0	1	0	0	0	0	0	0	0	0
147	12	2	4	4	0	0	1	0	1	0	0	0	0	1	0	0	0
148	50	7	11	16	10	15	7	8	6	6	8	9	2	8	3	3	43
149	49	6	11	16	10	14	7	9	6	6	8	9	2	8	3	4	38
150	58	7	11	16	10	15	7	9	6	6	8	9	2	8	3	4	45
151	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	56
152	735	169	126	96	69	33	42	42	17	14	20	21	27	20	14	13	133
153	39	2	2	2	0	0	0	0	0	2	0	0	0	0	0	0	10
154	70	11	5	10	15	1	5	4	3	4	2	3	4	3	10	0	39
155	12	0	3	3	1	1	0	3	4	1	0	0	1	4	1	2	68
156	9	2	3	3	0	0	1	0	1	0	0	0	0	1	0	0	0
157	58	7	11	16	10	15	7	9	6	6	8	9	2	8	3	4	39
158	9	0	3	1	1	1	0	3	3	0	0	0	1	1	1	2	57
159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
161	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
162	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
163	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
164	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
165	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
166	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
167	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
168	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
169	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
171	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
172	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
173	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
174	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
175	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
176	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
177	31	4	0	3	10	0	5	2	3	0	2	6	7	0	3	0	14
178	104	8	3	5	14	0	5	3	3	2	2	7	8	0	4	0	27
179	14	4	6	0	1	1	0	0	0	0	0	0	0	0	0	0	0
180	2	0	1	0	0	0	0	2	0	0	0	0	0	0	0	1	23
181	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
182	720	152	111	89	59	33	33	39	16	14	17	21	26	17	14	13	136
183	629	145	104	110	67	28	47	35	23	10	19	21	31	17	14	11	113

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
184	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
185	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
186	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
187	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
189	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
190	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
191	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	3
192	0	0	0	0	0	0	0	0	0	0	1	0	2	1	0	1	4
193	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
194	359	70	52	48	43	28	28	33	12	5	6	14	19	12	13	11	128
195	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
196	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
197	0	0	0	0	0	0	0	0	0	0	1	0	2	1	0	1	4
198	1	0	0	0	0	0	0	0	1	1	0	0	2	0	0	0	114
199	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	67
200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
201	9	4	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0
202	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
203	8	3	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0
204	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
205	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
206	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
207	0	0	0	0	0	0	0	0	0	0	1	0	2	1	0	1	4
208	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
209	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
210	9	2	1	4	0	0	0	0	0	0	0	0	0	1	0	0	0
211	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
212	43	11	11	17	6	1	5	0	6	3	3	1	2	3	2	1	54
213	7	0	5	0	0	1	1	0	4	0	0	0	0	1	0	0	0
214	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	31
215	0	0	0	1	0	0	0	1	1	0	0	0	0	2	2	0	67
216	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
217	17	3	5	6	2	3	2	0	5	2	1	3	2	3	1	1	7
218	32	2	6	11	7	0	1	0	2	0	0	0	0	0	2	0	12
219	15	2	5	6	1	1	1	0	4	2	1	3	1	1	0	1	7
220	27	2	5	10	5	0	1	0	0	0	0	0	0	0	0	0	0
221	33	7	6	15	6	1	4	0	2	3	3	1	2	2	2	1	47

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
222	48	11	12	19	7	2	5	0	7	3	3	1	2	3	4	1	57
223	47	8	10	18	7	1	4	0	7	4	4	4	2	3	3	1	56
224	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	13
225	38	7	6	18	6	0	3	0	2	3	3	1	1	0	2	1	48
226	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1
227	0	0	0	0	0	0	0	0	0	0	1	0	2	1	0	1	4
228	23	2	5	8	5	0	0	0	0	0	0	0	0	0	0	0	0
229	16	5	5	5	1	2	1	0	4	0	0	0	0	1	0	0	0
230	7	4	2	1	0	1	1	0	0	0	0	0	0	1	0	0	0
231	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
232	49	11	12	19	7	2	4	0	7	3	3	1	2	3	4	1	57
233	46	8	12	19	7	0	4	0	7	3	3	1	2	3	4	1	57
234	12	1	4	1	0	0	0	0	4	0	0	0	0	1	0	0	0
235	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
236	28	4	9	13	7	0	0	0	6	0	0	0	0	1	1	0	10
237	17	5	0	1	3	13	3	2	1	5	3	3	4	4	6	6	1219
238	9	2	1	0	1	0	0	2	2	2	0	2	3	0	0	0	168
239	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	7
240	5	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
241	134	19	24	19	9	16	11	5	5	4	6	6	5	3	3	4	442
242	145	16	9	11	4	5	10	5	0	0	1	1	0	3	2	0	19
243	30	0	3	0	0	3	0	0	0	1	0	0	0	0	0	0	1
244	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	37
245	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
246	193	20	11	3	1	2	2	4	0	1	1	0	0	0	0	0	14
247	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
248	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
249	438	56	57	72	29	33	28	14	6	7	12	10	6	9	9	8	638
250	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
251	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
252	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
253	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
254	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
255	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
256	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
257	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
258	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
259	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
260	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
261	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
262	1	2	1	1	1	0	0	0	2	1	1	1	0	0	0	0	1
263	3	2	0	0	1	0	0	0	0	0	1	1	3	0	0	0	0
264	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
265	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
266	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
267	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
268	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
269	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
270	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
271	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
272	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
273	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
274	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
275	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
276	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
277	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
278	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
279	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
280	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
281	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
282	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
283	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
284	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
285	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
286	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
287	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
288	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
289	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
290	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
291	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
292	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
293	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
294	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
295	1	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	1
296	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
297	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
298	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
299	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
301	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
303	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
304	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
305	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
306	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
307	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
308	9	4	3	2	4	5	0	6	6	4	1	0	2	1	0	0	2
309	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
310	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
311	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
312	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
313	0	0	0	0	0	1	1	2	0	0	1	0	0	0	1	0	25
314	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
315	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
316	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
317	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
318	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
319	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
321	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
322	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
323	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
324	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table D-4. Potentially intersecting well count by salinity bin (in parts per thousand total dissolved solids) for wells between 7,500 and 10,000 feet deep for the 325 NatCarb 2008 based polygons used in WECSsim.

Note: See Table C-1 to cross reference FID to polygon name. Table indicates the number of wells with depth between 7,500 feet and 10,000 feet in the following salinity bins.

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
1	44	9	7	13	16	25	13	17	43	85	8	3	14	5	7	9	660
2	29	0	3	0	0	1	0	0	0	1	1	1	0	0	0	0	154
3	64	14	14	19	28	36	14	25	50	93	18	10	20	13	16	16	1050
4	29	1	3	0	0	2	1	0	0	2	2	1	0	1	0	0	309
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	3	3	0	2	0	0	1	2	1	1	0	0	0	0	0	1	73
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	40	7	8	11	12	15	5	10	14	12	11	8	12	7	20	17	1018
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48
24	1	0	1	0	1	0	0	2	0	0	0	0	0	1	0	0	14
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	10	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1
31	20	4	5	0	3	0	4	1	0	1	0	0	0	0	1	0	4

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
32	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	15	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	180	9	4	2	6	0	2	0	2	3	0	0	2	1	2	1	0
37	286	11	2	0	0	1	4	0	0	0	1	0	0	0	2	0	7
38	197	15	4	2	6	0	2	0	2	3	0	0	2	1	2	1	0
39	5	0	0	0	1	3	2	1	0	2	3	4	0	2	3	2	327
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	8	1	3	0	1	5	3	0	0	4	3	5	3	4	6	4	556
44	4	1	3	0	1	4	3	0	0	2	2	4	3	2	6	3	514
45	5	1	2	0	1	3	3	1	1	4	4	6	3	4	6	4	457
46	12	0	2	3	16	11	2	1	0	1	1	1	0	0	0	0	42
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	17	3	0	0	3	6	3	4	1	0	0	0	0	0	0	0	11
49	17	6	3	3	0	1	0	9	0	2	0	3	0	2	0	0	27
50	105	19	4	8	11	3	3	7	3	1	0	0	0	0	0	3	1
51	18	4	2	0	8	0	4	0	0	0	0	0	0	0	0	0	0
52	2	0	0	0	0	0	4	1	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	1
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	82	12	11	0	14	2	0	4	13	9	4	4	6	0	1	1	55
56	42	11	15	13	15	17	16	13	13	8	11	13	10	5	5	3	532
57	42	11	15	13	15	17	16	13	13	8	11	13	10	5	5	3	532
58	42	11	15	13	15	17	16	13	13	8	11	13	10	5	5	3	532
59	29	9	12	7	14	14	13	7	11	6	11	11	9	4	5	3	517
60	4	2	3	1	3	2	2	0	2	1	4	5	2	1	2	2	330
61	0	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	169
62	114	19	25	13	18	20	3	2	0	1	0	0	1	0	0	2	3
63	28	6	3	5	2	1	2	1	0	0	0	1	0	0	1	0	8
64	80	9	7	9	20	12	8	20	9	6	8	4	5	6	3	1	181
65	101	15	10	14	21	13	10	21	9	6	9	5	5	6	4	1	184
66	133	27	30	24	25	15	10	16	8	6	9	5	4	6	4	0	176
67	5	1	2	0	1	3	3	1	0	4	3	6	2	4	5	4	417
68	362	20	4	0	2	1	4	0	0	3	1	0	2	1	4	1	7
69	9	4	2	0	3	8	2	0	0	1	0	0	0	0	0	0	38

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
70	1	3	0	4	0	0	3	0	0	0	0	0	0	0	0	0	0
71	13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72	8	2	5	3	3	1	1	5	2	4	4	1	6	2	11	4	269
73	4	1	3	0	1	4	3	0	0	4	3	5	3	4	6	4	523
74	5	1	3	0	1	4	3	1	0	4	3	6	3	4	6	4	525
75	3	1	3	0	1	6	3	0	0	2	3	4	3	2	6	3	499
76	15	2	6	3	3	1	1	5	2	5	5	2	7	3	11	4	361
77	138	21	15	18	21	14	10	21	9	6	9	5	5	6	4	1	184
78	16	2	2	4	1	1	0	1	0	0	0	1	0	0	1	0	1
79	15	4	1	1	1	1	2	0	0	0	0	0	0	0	0	0	33
80	50	8	6	8	17	12	7	14	6	3	5	4	2	3	0	1	145
81	26	3	2	5	9	5	2	5	0	0	0	1	1	0	1	1	10
82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
94	5	1	3	0	1	4	3	1	0	4	3	6	3	4	6	4	557
95	5	1	3	0	1	4	3	1	0	4	3	6	3	4	6	4	552
96	5	1	3	0	1	4	3	0	0	4	3	5	3	4	6	4	555
97	11	1	3	1	3	1	1	4	0	5	2	2	3	2	7	2	317
98	38	8	3	7	5	4	7	12	15	11	12	11	6	3	1	1	41
99	38	8	3	7	5	4	7	12	15	11	12	12	6	3	1	1	41
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
101	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
102	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
103	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
105	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
107	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
111	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
112	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
113	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
114	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
115	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
116	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
117	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
118	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
119	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120	3	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	5
121	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
122	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
123	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
124	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
125	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
126	3	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	5
127	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
128	14	6	4	2	3	1	2	2	2	0	0	2	0	0	0	1	3
129	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	6
130	11	3	3	1	0	0	1	1	2	0	0	1	0	0	0	0	6
131	10	3	1	0	1	1	1	1	1	0	0	1	0	0	0	1	3
132	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3
133	12	6	5	1	2	0	2	2	2	0	0	1	0	0	0	0	4
134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
135	0	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0
136	12	0	5	1	3	2	0	1	2	0	0	0	0	0	0	0	2
137	19	6	6	3	3	1	2	2	3	0	0	2	0	0	0	1	6
138	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3
139	6	2	0	1	1	0	0	0	0	2	0	0	0	0	0	0	6
140	2	2	0	1	0	0	0	0	0	2	0	0	0	0	0	0	6
141	14	2	5	2	4	2	0	1	2	2	0	0	0	0	0	0	12
142	14	2	5	2	4	2	0	1	2	2	0	0	0	0	0	0	11
143	2	2	0	1	0	0	0	0	0	2	0	0	0	0	0	0	11
144	8	0	3	1	2	0	0	0	0	0	0	0	0	0	0	0	9
145	2	2	0	1	0	0	0	0	0	2	0	0	0	0	0	0	10

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
146	10	0	3	1	3	2	0	0	2	0	0	0	0	0	0	0	0
147	12	0	4	1	3	2	0	1	2	0	0	0	0	0	0	0	0
148	10	0	3	1	3	2	0	0	2	0	0	0	0	0	0	0	2
149	12	0	4	1	3	2	0	1	2	0	0	0	0	0	0	0	5
150	14	2	5	2	4	2	0	1	2	2	0	0	0	0	0	0	11
151	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
152	626	102	49	47	48	41	11	22	20	18	17	9	9	3	2	30	163
153	21	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2	4
154	22	0	0	4	0	0	0	5	0	2	0	3	0	2	0	0	29
155	6	2	3	2	2	2	0	0	2	2	0	0	0	0	0	0	13
156	12	0	4	1	3	2	0	1	2	0	0	0	0	0	0	0	0
157	12	0	5	1	3	2	0	1	2	0	0	0	0	0	0	0	2
158	2	2	0	1	0	0	0	0	0	2	0	0	0	0	0	0	12
159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
160	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
161	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
162	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
163	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
164	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
165	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
166	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
167	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
168	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
169	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
171	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
172	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
173	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
174	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
175	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
176	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
177	11	3	3	1	0	0	0	2	0	2	0	1	0	2	0	0	39
178	47	3	3	3	0	0	0	2	3	10	0	3	3	2	0	2	50
179	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180	6	2	3	2	1	2	0	0	2	2	0	0	0	0	0	0	10
181	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
182	567	99	47	49	61	43	14	22	21	19	17	10	9	3	2	31	166
183	549	88	44	36	40	31	9	20	18	17	16	9	8	2	2	28	106

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
184	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
185	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
186	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
187	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
189	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
190	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
191	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	17
192	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
193	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
194	113	18	8	13	6	8	3	16	5	12	3	8	6	3	0	3	64
195	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
196	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
197	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1
198	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
199	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
201	7	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
202	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
203	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
204	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
205	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
206	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
207	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
208	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
209	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
210	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
211	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
212	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
213	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
214	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
215	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
216	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
217	3	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	3
218	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	7
219	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
220	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
221	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
222	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	10
223	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	10
224	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
225	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
226	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
227	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
228	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
229	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
230	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
231	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
232	3	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	8
233	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	8
234	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
235	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
236	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	3
237	22	7	7	10	13	12	12	13	15	4	13	8	2	6	5	4	278
238	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	35
239	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	12
240	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
241	51	8	13	12	25	23	13	16	10	11	11	13	8	3	3	3	532
242	27	3	5	6	5	3	4	10	5	2	4	0	3	3	2	0	99
243	4	3	1	1	1	0	1	0	0	0	0	0	0	0	0	0	1
244	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	43
245	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
246	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
247	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
248	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
249	137	20	28	24	36	28	24	31	21	17	21	20	16	10	9	5	994
250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
251	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
252	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
253	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
254	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
255	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
256	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
257	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
258	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
259	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
260	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
261	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
262	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
263	1	2	0	2	2	2	1	0	0	0	1	0	0	0	1	0	0
264	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
265	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
266	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
267	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
268	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
269	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
270	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
271	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
272	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
273	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
274	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
275	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
276	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
277	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
278	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
279	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
280	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
281	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
282	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
283	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
284	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
285	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
286	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
287	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
288	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
289	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
290	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
291	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
292	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
293	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
294	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
295	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
296	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
297	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NatCarb FID	0 to 10 ppt	10 to 12 ppt	12 to 14 ppt	14 to 16 ppt	16 to 18 ppt	18 to 20 ppt	20 to 22 ppt	22 to 24 ppt	24 to 26 ppt	26 to 28 ppt	28 to 30 ppt	30 to 32 ppt	32 to 34 ppt	34 to 36 ppt	36 to 38 ppt	38 to 40 ppt	> 40 ppt
298	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
299	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
301	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
303	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
304	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
305	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
306	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
307	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
308	2	1	0	0	0	1	0	1	1	0	1	2	0	1	0	1	0
309	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
310	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
311	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
312	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
313	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
314	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
315	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
316	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
317	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
318	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
319	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
321	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
322	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
323	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
324	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX E: POLYGON CLASSIFICATION SCHEME FOR WECSSIM

One of the fundamental requirements of WECSsim is an ability to estimate size and quality of deep (> 760 m) geologic formations underlying the United States as potential targets for permanent storage of supercritical CO_2. Parameters necessary to quantify pore space in the 325-NatCarb-2008-based polygons (see Appendix B) include polygon area, thickness, and porosity. Parameters necessary to predict the behavior of CO_2 injected into the polygon include polygon permeability, temperature, and pressure, the last two of which are calculated from polygon depth. Finally, identifying the salinity of pore water in the polygon is important for legal (below 10 ppt these waters may be potential potable water sources) and economic reasons (beyond 40 ppt the waters become relatively expensive to treat for power plant cooling). Polygon area estimates are discussed in Appendix C. Estimates of polygon thickness, depth, temperature, and pore water salinity are discussed in Appendix D. This appendix summarizes geologic data aggregation and analysis used to assign a porosity and permeability distribution to each NatCarb polygon.

E.1 Limitations of Available Data for NatCarb Polygons

WECSsim requires geologic and fluid flow-related data for each polygon of the NatCarb database in order to estimate the CO_2 storage and water extraction resources of the U.S. To facilitate injection flow rate calculations, these data include probability distribution functions (pdfs) of absolute permeability, porosity, and the spatial structure properties of the geologic formation in terms of the nugget, sill, and range of the semivariogram of porosity. As discussed in Appendix B, the publically available NatCarb 2008 database contains neither porosity nor permeability data. Correspondence with the Regional CO_2 Partnerships and literature searches resulted in the acquisition of some porosity data (176 out of 325 or ~ 54% of the polygons), but neither permeability nor spatial structure data.

Based on additional literature searches of 35 of the 325 polygons, required data (i.e., porosity and permeability) were not, during the duration of this project, readily available in one location. Journal articles, USGS reports, and various other publications typically report ranges or minimum and maximum values of permeability and porosity for a particular formation. Permeability and porosity are not commonly reported as pdfs. Other than the spatial structure information for the Mount Simon Formation (Finley, 2005), no additional semivariogram data of this type has been found for the other polygons. Another difficultly is that the NatCarb polygons often identify geologic formations or groups of formations that are composed of a variety of different lithologies (i.e., sandstone, mudstone, carbonate, etc.). Thus, polygons often do not represent a single lithologic rock type, and the available data describe the formations associated with polygons using ranges (i.e., minimum and maximum values; not to be confused with semivariogram ranges) of porosity and permeability values that are not described in a statistically meaningful way in terms of pdfs.

E.2 Lithologic Classification Approach

Our approach for coping with the polygon data limitations is based on assigning the polygons to a small set of rock types with well defined (i.e., quantitative) properties in terms of porosity and permeability pdfs and spatial structure properties (i.e., nugget, sill, and ranges of a semivariogram). The data for four rock types presented below were incorporated into WECSsim to estimate flow rates. Thus, WECSsim is able to perform the flow rate calculations for all the polygons based on the small number of rock types.

The polygons were classified into two groups or tiers based on the degree of "epistemic uncertainty" or the relative amount of knowledge available for the polygon properties. Tier 1 polygons are those of the recent literature searches that required porosity, permeability, or both ranges. In some cases, the articles or reports explicitly give the data ranges. In other cases, graphs present the data as functions of depth, which require further evaluation (e.g., via visually estimating the information to obtain the data ranges). These polygons also now include lithologic information in terms of four general rock types:

1) Clean sandstone
2) Dirty sandstone
3) Carbonate
4) Gulf Coast

The lithologic information for Tier 1 polygons comes from formation descriptions within the published literature. Many of the polygons cover a large region and represent a number of depositional environments over an extensive period of time. Accordingly, the polygons may be considered a combination of multiple rock types by estimating the relative percentage of the rock types (i.e., 75% clean sandstone; 25% carbonate). The lithologic description is not based on a rigorous examination of well logs or other quantitative data. Rather, they come from a general estimation of available qualitative or quantitative formation descriptions associated with the polygons. Thus, the rock type percentages are descriptive, although they are given as a quantitative percentage.

Tier 2 polygons are those lacking porosity and permeability ranges. However, these polygons have still been associated with the rock type percentages. In this case, adapting region-specific geological information for the polygons was used to assign the rock types. Thus, the rock type description for Tier 2 polygons has lower certainty for its assigned parameters than the Tier 1 polygons.

E.3 Quantitative Construction of Rock Types

Ideally, the rock types would be based solely on data from the NatCarb 2008 polygons. However, a literature search returned porosity or permeability data on only 35 polygons, and these are not commonly of one lithology. Thus, data on end-member rock types is very limited. (Table E-1 gives the end-member data and corresponding number of polygons.) Thus, the analysis employs the lithologic and porosity and permeability ranges of the Tier 1 polygons along with supplemental rock type data from the literature (see Table E-1) to quantify the permeability and porosity for the various rock types. Table E-2 presents the quantitative definition of the rock types.

Additionally, the porosity and permeability rock types are supplemented by spatial structure information from Finley (2005) for the Mount Simon Sandstone (as a Dirty Sandstone with mean permeability of 29.7 mD) and the geosciences literature focusing on lithologic rock types (e.g., Hoeksema and Kitanidis, 1985). Note that the semivariogram (i.e., spatial structure) data should be considered only a first approximation due to difficulty in relating the rock types from the literature (Hoeksema and Kitanidis, 1985) to the rock types from the permeability and porosity data. Thus, the semivariogram data for the Mount Simon Sandstone is used for the Dirty Sandstone, and the semivariogram values for the other rock types are referenced from the Mount Simon Sandstone according to expected variation in the properties. Using the work presented in Hoeksema and Kitanidis (1985) and others could help refine the data presented in Table E-2 in future studies.

The permeability and porosity ranges of Table E-2 are converted to pdfs through the following assumptions:

- arithmetic porosity values are assumed to be normally distributed;
- the $\log_{10}$ transformation of permeability values is assumed to be normally distributed; and
- the data ranges for porosity and $\log_{10}$ permeability are assumed to fall near the upper and lower tails of the normal distributions.

Previous work indicated that permeability data for geologic formations are typically $\log_{10}$ normal (Hoeksema and Kitanidis, 1985). Thus, the analysis assumes that the minimum and maximum values of the ranges fall somewhere near the tails of the $\log_{10}$-normal distributions. Future work and a larger study scope might consider looking to obtain sample data (e.g., number of core plugs for porosity measurements), the depth of the samples, and other information to determine specific values for the assumed $\log_{10}$-normal distributions and the applicability of using this $\log_{10}$ assumption itself.

To facilitate immediate implementation of the rock types into WECSsim, the analysis assumes the mean of each pdf is the average value, respectively, of the minimum and maximum values of the ranges of porosity and $\log_{10}$ permeability. (In this context, range refers to minimum and maximum data values and not the range of a semivariogram.) The analysis assumes the minimum and maximum values of the ranges of porosity and $\log_{10}$ permeability fall two to three standard deviations away from the mean of the range. The two-standard-deviation case means that the analysis assumes the ranges capture 95% of the possible probability values for the rock type in question. The three-standard-deviation case contains 99.7% of the possible probability values. See Table F-2 for the summary of standard deviations for the rock types.

WECSsim implements the equation of a normal probability distribution function defined with a mean and standard deviation (Table F-2) to allow WECSsim to dynamically generate $\log_{10}$ permeability and arithmetic porosity probability distribution functions based on the WECSsim user's choice of standard deviation. Such generation of pdfs allows the user to choose ranges of data that can be used in the various different methods for estimating CO_2 injection and brine production. Thus, the user will not be limited to the static information in Table F-2.

Table E-1. Permeability and porosity data with corresponding rock types.

Rock Type	Permeability Min. mD	Permeability Max. mD	Porosity Min. %	Porosity Max. %	Source
Clean Sandstone	20	1000	8	18	Literature search based on 2 NatCarb Polygons
Dirty Sandstone	0.22	0.5	9	27	Literature search based on 1 NatCarb Polygon
Gulf Coast	0.6	54	1.2	15	Literature search based on 1 NatCarb Polygon
Carbonate	5	28	24.5	28	Literature search based on 1 NatCarb Polygon
Sandstone	0.03	621	0.5*	10*	Domenico and Schwartz, 1998
Sandstone	0.01	311	5.0	30	Freeze and Cherry, 1979
Siltstone	0.00	1.45	21	41	Domenico and Schwartz, 1999
Limestone, dolomite	0.10	621	0.1*	5*	Domenico and Schwartz, 2000
Limestone, dolomite	0.07	311	0	20	Freeze and Cherry, 1979

*Value is for effective porosity (interconnected pore space), not total porosity.

Note: The first four rock types are based on NatCarb polygons that are composed of 100% of the rock type in question. Most of the NatCarb with permeability and porosity data from the recent literature search, however, were composed of more than one rock type.

Table E-2. Quantitative definition of the four rock types.

				Permeability (mD)			
Rock Type	min.	max.	$\log_{10}$ min.	$\log_{10}$ max.	$\log_{10}$ mean	σ for min. & max. at 3σ	σ for min. & max. at 2σ
Clean Sandstone	100	1000	2	3	2.5	0.1684	0.2551
Dirty Sandstone	0.01	100	-2	2	0.0	0.6734	1.0204
Gulf Coast	0.6	54	-0.22	1.73	0.8	0.329	0.4985
Carbonate	0.07	621	-1.15	2.79	0.8	0.6646	1.0071

Porosity

Rock Type	min.	max.	mean	σ for min. & max. at 3σ	σ for min. & max. at 2σ
Clean Sandstone	0.08	0.18	0.130	0.0168	0.0255
Dirty Sandstone	0.09	0.27	0.18	0.0303	0.0459
Gulf Coast	0.012	0.15	0.081	0.0232	0.0352
Carbonate	0.001	0.28	0.1405	0.0470	0.0712

Semivariogram

Rock Type	Nugget	Sill	Horizontal Range (m)	Vertical Range (m)	Porosity-permeability coefficient r
Clean Sandstone	0.2	0.8	15,000	10	0.6
Dirty Sandstone	0.26	0.74	2,000	4	0.5
Gulf Coast	0.3	0.7	1,500	3	0.4
Carbonate	0.22	0.78	32,348	7	0.55

Note: Nugget and sill values were scaled such that their total equals 1 for input into GSLIB (Deutsch and Journel, 1988). The dirty sandstone uses the nugget, sill, and range values from Finley (2005) for the Mount Simon Formation.

The validity of the polygon classification assignment depends on several factors, including the proper identification of a characteristic of the polygons that allows grouping of the polygons, properly estimating permeability and porosity values, and proper identification of geostatistical properties. These factors are difficult to assess due to the paucity of data. WECSsim is thus flexible in assessing and using property pdfs so that sensitivities of cost and other variables can be explored as a function of the geologic properties. Table E-3 illustrates the rock types assigned to each formation for the interested reader.

Table E-3. Formations according to the four rock types.

NatCarb Partner-ship	Basin Name	Formation	% Clean Sand-stone	% Dirty Sand-stone	% Lime-stone	% Gulf Coast
SECARB	Cedar Keys Lawson Fm	Cedar Keys Lawson Fm	0%	0%	100%	0%
SECARB	GULF COAST	Eocene Sand	0%	0%	0%	100%
SECARB	GULF COAST	Tertiary Undivided	0%	0%	0%	100%
SECARB	GULF COAST	Oligocene	0%	75%	10%	15%
SECARB	Tuscaloosa Group	Tuscaloosa Group	25%	75%	0%	0%
SECARB	Offshore Atlantic	None	0%	0%	0%	100%
SECARB	Offshore Atlantic	None	0%	0%	0%	100%
SECARB	Woodbine & Paluxy Fm	Woodbine & Paluxy Fm	25%	75%	0%	0%
MGSC	Illinois Basin	Cypress SS	25%	75%	0%	0%
MGSC	Illinois Basin	Mt. Simon SS	0%	100%	0%	0%
MGSC	Illinois Basin	St. Peter SS	100%	0%	0%	0%
SECARB	GULF COAST	Olmos	0%	100%	0%	0%
SECARB	GULF COAST	Pliocene	100%	0%	0%	0%
SECARB	Potomac Group	Potomac Group1	0%	100%	0%	0%
SECARB	Potomac Group	Potomac Group2OS	0%	100%	0%	0%
SECARB	Potomac Group	Potomac Group2	0%	100%	0%	0%
SECARB	Potomac Group	Potomac Group1OS	0%	100%	0%	0%
SECARB	Pottsville Fm	Pottsville Fm	0%	0%	0%	100%
SECARB	South Carolina-Georg	Triassic, Tuscaloosa	30%	70%	0%	0%
MRCSP	Coastal Plains	None	0%	100%	0%	0%
SECARB	GULF COAST	Miocene	25%	75%	0%	0%
SECARB	Mt. Simon SS	Mt. Simon SS	0%	100%	0%	0%
MRCSP	Michigan Basin	None	0%	30%	70%	0%
MRCSP	Appalachian Basin	None	0%	25%	75%	0%
MRCSP	Fold and Thrust Belt	None	0%	70%	30%	0%
Big Sky	Montana Thrust Belt	Imbricate Thrust Gas	0%	100%	0%	0%
Big Sky	North-Central Montana	Jurassic-Cretaceous	0%	100%	0%	0%
Big Sky	North-Central Montana	Shallow Cretaceous B	0%	100%	0%	0%
Big Sky	Southwest Montana	Crazy Mountains and Lake Basins	0%	100%	0%	0%
Big Sky	Southwest Montana	Nye-Bowler Wrench Zo	0%	100%	0%	0%
Big Sky	Big Horn Basin	Deep Basin Structure	0%	0%	20%	80%
Big Sky	Big Horn Basin	Phosphoria	80%	0%	20%	0%
Big Sky	Wind River Basin	Basin Margin Subthru3	0%	100%	0%	0%
Big Sky	Wind River Basin	Basin Margin Subthru	0%	100%	0%	0%
Big Sky	Wind River Basin	Basin Margin Subthru2	0%	100%	0%	0%
Big Sky	Wind River Basin	Basin Margin	0%	100%	0%	0%

NatCarb Partner-ship	Basin Name	Formation	% Clean Sand-stone	% Dirty Sand-stone	% Lime-stone	% Gulf Coast
		Anticli				
Big Sky	Wind River Basin	Basin Margin Anticli2	0%	100%	0%	0%
Big Sky	Wind River Basin	Deep Basin Structure	0%	100%	0%	0%
Big Sky	Wind River Basin	Muddy Sandstone Stra	0%	100%	0%	0%
Southwest	Permian	Montoya	0%	0%	100%	0%
MRCSP	Arches Province	None	0%	0%	100%	0%
Big Sky	North-Central Montana	Fractured-Faulted Ca	0%	0%	100%	0%
Big Sky	North-Central Montana	Tyler Sandstone	50%	0%	50%	0%
Southwest	Permian	Pennsylvanian	0%	25%	75%	0%
Southwest	Permian	San Andres	0%	25%	75%	0%
Southwest	Permian	Siluro-Devonian	0%	40%	60%	0%
Big Sky	Wyoming Thrust Belt	Hogsback Thrust	0%	10%	90%	0%
Big Sky	Wyoming Thrust Belt	Cretaceous Stratigra	0%	25%	75%	0%
Big Sky	Southwestern Wyoming	Rock Springs Uplift	30%	50%	20%	0%
Big Sky	Southwestern Wyoming	Cherokee Arch	20%	60%	20%	0%
Big Sky	Southwestern Wyoming	Moxa Arch-LaBarge	20%	60%	20%	0%
Big Sky	Southwestern Wyoming	Basin Margin Anticli	0%	80%	20%	0%
Big Sky	Southwestern Wyoming	Basin Margin Anticli2	0%	80%	20%	0%
Big Sky	Southwestern Wyoming	Basin Margin Anticli3	0%	80%	20%	0%
Big Sky	Southwestern Wyoming	Basin Margin Anticli4	0%	80%	20%	0%
Big Sky	Southwestern Wyoming	Platform	30%	40%	30%	0%
Big Sky	Williston Basin	Madison (Mississippi)	0%	0%	100%	0%
Big Sky	Williston Basin	Red River (Ordovicia)	0%	20%	80%	0%
Big Sky	Williston Basin	Middle and Upper Dev	0%	20%	80%	0%
Big Sky	Williston Basin	Pre-Prairie Middle D	0%	20%	80%	0%
Big Sky	Williston Basin	Post-Madison through	0%	80%	20%	0%
Big Sky	Williston Basin	Pre-Red River Gas	100%	0%	0%	0%
Big Sky	Powder River Basin	Basin Margin Anticli	25%	50%	25%	0%
Big Sky	Powder River Basin	Leo Sandstone	40%	20%	40%	0%

NatCarb Partner-ship	Basin Name	Formation	% Clean Sand-stone	% Dirty Sand-stone	% Lime-stone	% Gulf Coast
Big Sky	Powder River Basin	Upper Minnelusa Sand	60%	20%	20%	0%
Big Sky	Powder River Basin	Lakota Sandstone	0%	100%	0%	0%
Big Sky	Powder River Basin	Fall River Sandstone	0%	100%	0%	0%
Southwest	Permian	Simpson	0%	80%	20%	0%
Big Sky	Wind River Basin	Shallow Tertiary - U	25%	75%	0%	0%
Big Sky	Wyoming Thrust Belt	Moxa Arch Extension	0%	30%	70%	0%
Big Sky	Wyoming Thrust Belt	Absaroka Thrust	50%	10%	40%	0%
Big Sky	North-Central Montana	Devonian-Mississippi	0%	0%	100%	0%
Southwest	Permian	San Andres Limeston	0%	20%	80%	0%
Southwest	Permian	Triassic	0%	100%	0%	0%
Southwest	Permian	Upper_Guadalupe	0%	20%	80%	0%
Southwest	Permian	Wolfcamp	0%	0%	100%	0%
Southwest	Permian	Morrison Formation	0%	80%	20%	0%
Big Sky	Powder River Basin	Muddy Sandstone	0%	100%	0%	0%
Big Sky	Powder River Basin	Deep Frontier Sandst	0%	100%	0%	0%
Big Sky	Powder River Basin	Turner Sandstone	0%	100%	0%	0%
Big Sky	Powder River Basin	Sussex-Shannon Sands	0%	100%	0%	0%
Big Sky	Powder River Basin	Mesaverde-Lewis	0%	100%	0%	0%
Southwest	Navajo Power Plant	CEDAR MESA SANDSTONE	100%	0%	0%	0%
Southwest	Cholla Power Plant	NACO	0%	40%	60%	0%
Southwest	St. Johns-Springervi	GRANITE WASH	0%	100%	0%	0%
Southwest	Willcox basin	TERTIARY BASIN FILL	0%	100%	0%	0%
Southwest	Red Rock basin	TERTIARY BASIN FILL	0%	100%	0%	0%
Southwest	Higley basin	TERTIARY BASIN FILL	0%	100%	0%	0%
Southwest	Luke basin	BASIN FILL-EVAPORITE	0%	100%	0%	0%
Southwest	Tucson basin	TERTIARY EVAPORITES-	0%	100%	0%	0%
Southwest	Mohawk basin	TERTIARY BASIN FILL	0%	0%	100%	0%
Southwest	San Cristobal basin	TERTIARY BASIN FILL	30%	70%	0%	0%

NatCarb Partner-ship	Basin Name	Formation	% Clean Sand-stone	% Dirty Sand-stone	% Lime-stone	% Gulf Coast
Southwest	Navajo Power Plant	REDWALL LIMESTONE	0%	0%	100%	0%
Southwest	Navajo Power Plant	TAPEATS SANDSTONE	0%	100%	0%	0%
Southwest	Permian	Ellenburger	0%	0%	100%	0%
Southwest	Permian	Leonard	0%	100%	0%	0%
Southwest	Permian	Mississippian	0%	0%	100%	0%
Southwest	Permian	Devonian strata	0%	90%	10%	0%
Southwest	Denver	Lyons	100%	0%	0%	0%
Southwest	Denver	Morrison	0%	80%	20%	0%
Southwest	Raton	Carlile	0%	90%	10%	0%
Southwest	Raton	Dockum	0%	100%	0%	0%
Southwest	Raton	Forthayes	0%	0%	100%	0%
Southwest	Raton	Glorieta	100%	0%	0%	0%
Southwest	Raton/Denver	Codell	0%	100%	0%	0%
Southwest	Raton	Raton	0%	100%	0%	0%
Southwest	Raton	Graneros	0%	100%	0%	0%
Southwest	Raton	Dakota	0%	100%	0%	0%
Southwest	Raton	Entrada	100%	0%	0%	0%
Southwest	Raton	Sangre De Cristo	0%	100%	0%	0%
Southwest	Raton	Yeso	100%	0%	0%	0%
Southwest	Raton	Greenhorn	0%	0%	100%	0%
Southwest	Raton	Morrison	0%	80%	20%	0%
Southwest	Raton	Pierreshale	0%	100%	0%	0%
Southwest	Raton	Purgatoire	0%	100%	0%	0%
Southwest	Anadarko	Chester	0%	0%	100%	0%
Southwest	Raton	Smoky Hill Marl	0%	0%	100%	0%
Southwest	Anadarko	Arbuckle	0%	0%	100%	0%
Southwest	Anadarko	Atoka	0%	90%	10%	0%
Southwest	Raton	Trinidad	0%	100%	0%	0%
Southwest	Uinta	Dakota	0%	100%	0%	0%
Southwest	Anadarko	Desse/Cherokee	0%	80%	20%	0%
Southwest	Anadarko	Misener	0%	60%	40%	0%
Southwest	Anadarko	Morrow	0%	50%	50%	0%
Southwest	Anadarko	Simpson	0%	80%	20%	0%
Southwest	Anadarko	Viola	0%	0%	100%	0%
Southwest	Uinta	Entrada	100%	0%	0%	0%
Southwest	Uinta	Frontier2	0%	100%	0%	0%
Southwest	Uinta	Green River	0%	80%	20%	0%
Southwest	Uinta	Frontier1	0%	100%	0%	0%
Southwest	Uinta	Mancos	0%	90%	10%	0%
Southwest	Uinta	Uinta1	0%	80%	20%	0%
Southwest	Uinta	Kayenta	0%	90%	10%	0%
Southwest	Uinta	Mesaverde	0%	100%	0%	0%
Southwest	Uinta	Sego	0%	100%	0%	0%
Southwest	Uinta	Uinta2	0%	80%	20%	0%
Southwest	SanJuan	CliffHouse	0%	100%	0%	0%
Southwest	Uinta	Wasatch	0%	100%	0%	0%
Southwest	Uinta	White Rim/Coconino	100%	0%	0%	0%

NatCarb Partner-ship	Basin Name	Formation	% Clean Sand-stone	% Dirty Sand-stone	% Lime-stone	% Gulf Coast
Southwest	SanJuan	Chinle	0%	100%	0%	0%
Southwest	SanJuan	DeChelley	0%	100%	0%	0%
Southwest	SanJuan	Entrada	100%	0%	0%	0%
Southwest	SanJuan	Dakota	0%	100%	0%	0%
Southwest	SanJuan	Elbert	0%	50%	50%	0%
Southwest	SanJuan	Leadville	0%	20%	80%	0%
Southwest	SanJuan	HonakerTrail	0%	0%	100%	0%
Southwest	SanJuan	Fruitland	0%	100%	0%	0%
Southwest	SanJuan	Lewis	0%	100%	0%	0%
Southwest	SanJuan	Mancos	0%	90%	10%	0%
Southwest	SanJuan	Menefee	0%	100%	0%	0%
Southwest	SanJuan	Morrison	0%	80%	20%	0%
Southwest	SanJuan	OrganRock	0%	100%	0%	0%
Southwest	Green River	Morrison	0%	80%	20%	0%
Southwest	Green River	Graneros	0%	100%	0%	0%
Southwest	Green River	Fort Hays	0%	0%	100%	0%
Southwest	SanJuan	Ouray	0%	0%	100%	0%
Southwest	SanJuan	PicturedCliffs	0%	100%	0%	0%
Southwest	SanJuan	PointLookout	0%	100%	0%	0%
Southwest	SanJuan	Rico	0%	50%	50%	0%
Southwest	Sierra Grande	Sangre De Cristo	0%	100%	0%	0%
Southwest	Plateau/Coconino	Navajo	100%	0%	0%	0%
Southwest	Plateau/Coconino	Coconino	100%	0%	0%	0%
Southwest	Pedregosa	El Paso	0%	20%	80%	0%
Southwest	Pedregosa	Percha	0%	0%	100%	0%
Southwest	Pedregosa	Montoya	0%	0%	100%	0%
Southwest	Pedregosa	Martin	0%	30%	70%	0%
Southwest	Palo Duro	Strawn	0%	0%	100%	0%
Southwest	Palo Duro	Clear Fork	0%	30%	70%	0%
Southwest	Palo Duro	Cisco	0%	50%	50%	0%
Southwest	Palo Duro	Canyon	0%	30%	70%	0%
Southwest	Orogrande	Yeso	100%	0%	0%	0%
Southwest	Orogrande	Montoya	0%	0%	100%	0%
Southwest	Orogrande	Fusselman	0%	0%	100%	0%
Southwest	Orogrande	El Paso	0%	20%	80%	0%
Southwest	Orogrande	Bliss	0%	100%	0%	0%
Southwest	Orogrande	Abo2	20%	80%	0%	0%
Southwest	Orogrande	Abo1	20%	80%	0%	0%
Southwest	Green River	Pierre	0%	100%	0%	0%
Southwest	Green River	Green River	0%	80%	20%	0%
Southwest	North Park	Dakota	0%	100%	0%	0%
Southwest	SanJuan	PinkertonTrail	0%	0%	100%	0%
Southwest	Paradox	Carmel4	0%	0%	100%	0%
Southwest	Green River	Dakota	0%	100%	0%	0%
Southwest	Green River	Carlile	0%	90%	10%	0%
Southwest	Estancia	Yeso	100%	0%	0%	0%
Southwest	Estancia	Todilto	0%	0%	100%	0%
Southwest	Estancia	Morrison	0%	80%	20%	0%
Southwest	Estancia	Mancos	0%	90%	10%	0%
Southwest	Estancia	Entrada	100%	0%	0%	0%

NatCarb Partner-ship	Basin Name	Formation	% Clean Sand-stone	% Dirty Sand-stone	% Lime-stone	% Gulf Coast
Southwest	Estancia	Dakota	0%	100%	0%	0%
Southwest	Estancia	Chinle	0%	100%	0%	0%
Southwest	Paradox	Cutler2	25%	0%	75%	0%
Southwest	Paradox	Carmel3	0%	0%	100%	0%
Southwest	Paradox	Carmel2	0%	0%	100%	0%
Southwest	Green River	Entrada	100%	0%	0%	0%
Southwest	Paradox	Carmel1	0%	0%	100%	0%
Southwest	Paradox	Entrada	100%	0%	0%	0%
Southwest	Paradox	Kayenta3	0%	100%	0%	0%
Southwest	Paradox	Cutler1	25%	0%	75%	0%
Southwest	Paradox	Moenkopi	0%	70%	30%	0%
Southwest	Paradox	Mancos	0%	90%	10%	0%
Southwest	Paradox	Navajo2	100%	0%	0%	0%
Southwest	Paradox	Kayenta1	0%	100%	0%	0%
Southwest	Paradox	Kayenta2	0%	100%	0%	0%
Southwest	Paradox	Kayenta4	0%	100%	0%	0%
Southwest	Paradox	Dakota	0%	100%	0%	0%
Southwest	Paradox	Morrison	0%	80%	20%	0%
Southwest	Paradox	Navajo3	100%	0%	0%	0%
Southwest	Paradox	Navajo1	100%	0%	0%	0%
Southwest	Paradox	Navajo4	100%	0%	0%	0%
Southwest	Piceance	Wasatch1	0%	100%	0%	0%
Southwest	Piceance	Wasatch2	0%	100%	0%	0%
Southwest	Piceance	Weber	50%	50%	0%	0%
Southwest	Piceance	Rollins	0%	100%	0%	0%
Southwest	Fort Worth Palo Duro	None	0%	100%	0%	0%
Southwest	Kansas Arbuckle Miss	None	0%	100%	0%	0%
Southwest	Paradox	Summerville1	0%	100%	0%	0%
Southwest	Piceance	Mancos	0%	90%	10%	0%
Southwest	Piceance	Maroon	0%	100%	0%	0%
Southwest	Piceance	Mesaverde	0%	100%	0%	0%
Southwest	Piceance	Minturn	0%	100%	0%	0%
Southwest	Piceance	Moenkopi	0%	70%	30%	0%
Southwest	Piceance	Morrison	0%	80%	20%	0%
Southwest	Piceance	Mowry	0%	100%	0%	0%
Southwest	Piceance	Parkcity	0%	10%	90%	0%
Southwest	Piceance	Shinarump	0%	100%	0%	0%
Southwest	Piceance	Statebridge	0%	100%	0%	0%
Southwest	Paradox	Summerville2	0%	100%	0%	0%
Southwest	Piceance	Belden	0%	70%	30%	0%
Southwest	Piceance	Corcoran	0%	100%	0%	0%
Southwest	Piceance	Cozzette	0%	100%	0%	0%
Southwest	South Park	Dakota	0%	100%	0%	0%
Southwest	Piceance	Dakota	0%	100%	0%	0%
Southwest	Piceance	Entrada	100%	0%	0%	0%
Southwest	Piceance	Fortunion	0%	100%	0%	0%
Southwest	Piceance	Greenriver	0%	80%	20%	0%
Southwest	Piceance	Leadville	0%	20%	80%	0%

NatCarb Partner-ship	Basin Name	Formation	% Clean Sand-stone	% Dirty Sand-stone	% Lime-stone	% Gulf Coast
Southwest	Oklahoma Basins	None	0%	50%	50%	0%
Southwest	Paradox	Ouray	0%	0%	100%	0%
PCOR	Williston Basin	Broom Creek	0%	80%	20%	0%
PCOR	Williston Basin	Lower Cretaceous4	0%	100%	0%	0%
PCOR	Williston Basin	Lower Cretaceous	0%	100%	0%	0%
PCOR	Williston Basin	Lower Cretaceous5	0%	100%	0%	0%
PCOR	Williston Basin	Lower Cretaceous3	0%	100%	0%	0%
PCOR	Williston Basin	Lower Cretaceous6	0%	100%	0%	0%
PCOR	Williston Basin	Lower Cretaceous2	0%	100%	0%	0%
PCOR	Denver	Lower CretaceousD	0%	100%	0%	0%
PCOR	Denver	Lower CretaceousD2	0%	100%	0%	0%
PCOR	Denver	Lower CretaceousD3	0%	100%	0%	0%
PCOR	Williston Basin	Madison	0%	0%	100%	0%

APPENDIX F: CO_2 INJECTIVITY METHODS

F.1 Analytical CO_2 Injectivity Approach

Given an injection well field design lifetime and an amount of CO_2 to store in a given NatCarb polygon, the goal of the CO_2 Storage Module of WECSsim is to estimate the number of injection wells and corresponding well spacing.

WECSsim considers two different injection regimes, one with injection only, and one in which brine[11] is extracted simultaneously from the target formation to increase CO_2 storage efficiency. The analytic solution of CO_2 flow into a porous media occupied by brine that is simultaneously being extracted is described below.

The analytical solution for injection–extraction assumes that the pressure radii of influence for both the CO_2 injectors and brine extractors are organized as shown in Figure F-1. This same packing pattern persists for greater numbers of CO_2 wells. The number of CO_2 wells in the total domain is:

$$N_{CO2} = n^2 + (n-1)^2 \quad \text{(F-1)}$$

where lower case n is the number of CO_2 wells on the bottom (or top) row. The n varies from 1, 2, 3, etc., and thus N_{CO2} is 1, 5, 13, 25, etc., for total well patterns of 1, 3x3, 5x5, 7x7, etc. For example, when n = 2 as in Fig. F-1, the analysis has the total well pattern of 3x3 (i.e., 9 total wells) with 5 CO_2 wells.

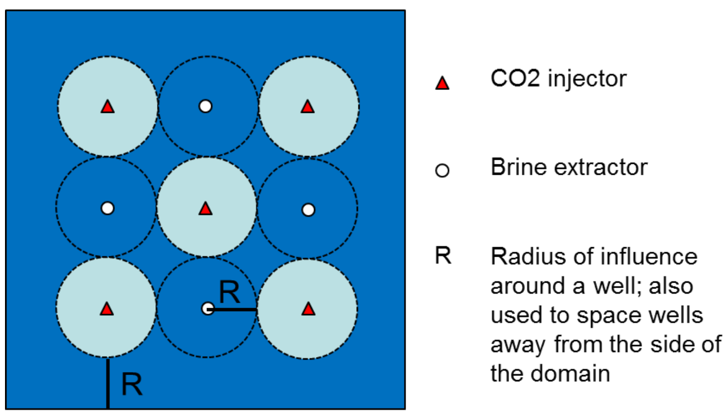

Figure F-1. Schematic of packing pattern for radii of influence for pressure due to injector and extractor wells.

Expanding N_{CO2} gives:

$$N_{CO2} = 2n^2 - 2n + 1 \quad \text{(F-2)}$$

The total area of the domain as a function of n is:

$$A = (n4R)^2 \quad \text{(F-3)}$$

[11] WECSsim targets saline formations because of EPA protection for pore water of salinity less than 10,000 parts per million total dissolved solids as potential drinking water; thus, the pore water is referred to here as brine.

where R is the pressure radius of influence (see Figure F-1). Note that A is the square area for the well field (see Figure F-1), which is a subarea of the NatCarb polygon. Solving Equation F-3 for n and plugging into Equation F-2 gives:

$$N_{CO2} = \frac{A}{8R^2} - \frac{\sqrt{A}}{2R} + 1 \qquad \text{(F-4)}$$

The number of CO_2 wells N_{CO2} can also be expressed as a function of the total volume of CO_2 injected and the volumetric CO_2 flow rate of a single well:

$$N_{CO2} = \left(\frac{Q_{CO2-total-mass}}{\rho_{CO2}}\right)\left(\frac{1}{Q_{CO2}}\right) \qquad \text{(F-5)}$$

where $Q_{CO2\text{-total-mass}}$ is average total mass injection rate (kg/s) over the lifetime of the project (i.e., 30 years was used here); ρ_{CO2} is density of CO_2 at reservoir conditions (kg/m^3); and Q_{CO2} is the volumetric CO_2 flow rate (m^3/s) for a single well. What is needed now is an expression for Q_{CO2}. The analysis employs an expression with several simplifying assumptions, which are then validated and modified (or "tuned") to approximately match results from the multiphase flow simulator TOUGH2-ECO2N equation of state (Pruess, 2005; see Section F.2). The analysis assumes if volumetrically equivalent amounts of CO_2 and brine are injected and extracted from the well field shown in Figure F-1, the edges of the radii of influence of each well will remain at constant initial pressure throughout the run. Assuming a cylindrical domain with constant pressure at both the center of the domain (i.e., the well) and the outer boundary (the edge of the radius of pressure influence of the well as shown in Figure F-1), the steady-state, single-phase-fluid Darcy flow equation is the following (see Vukovic and Soro, 1997):

$$Q = -2\pi r b\left(\frac{k\rho g}{\mu}\right)\frac{d\Pi}{dr} \qquad \text{(F-6)}$$

where Q is volumetric flow rate of the single phase fluid; r is the distance from the center of the well to the constant pressure boundary; b is the vertical height of the cylindrical reservoir; k is permeability (m^2); ρ is density (kg/m^3); g is gravity (m/s^2); μ is viscosity (Pa s); and Π is the hydraulic head (i.e., $z + P/(\rho g)$, with units of m, where z is elevation and P is pressure (N/m^2)). Assume an elevation datum such that $z = 0$. The boundary conditions are: at $r = r_0$ and $\Pi = P_{CO2}/(\rho g)$; and *at* $r = R$, $\Pi = P_0/(\rho g)$, where r_0 is the well bore radius; P_{CO2} is the pressure at the injector; and P_0 is the initial reservoir pressure (hydrostatic at the middle of the vertical thickness). Rearranging and solving for Q:

$$\int_{r_0}^{R}\frac{Q}{2\pi r b}\frac{\mu}{k\rho g}\,dr = -\int_{P_{CO2}/\rho g}^{P_0/\rho g} d\Pi \qquad \text{(F-7)}$$

$$ln\left(\frac{R}{r_0}\right)\frac{Q}{2\pi b}\frac{\mu}{k\rho g} = -\frac{(P_0 - P_{CO2})}{\rho g} \qquad \text{(F-8)}$$

$$Q = \frac{2\pi b k(P_{CO2} - P_0)}{\mu\, ln\left(\frac{R}{r_0}\right)} \qquad \text{(F-9)}$$

Letting $Q = Q_{CO2}$, and plugging Equation F-9 into Equation F-5, the analysis then has an expression that relates CO_2 flow rate, the radius of influence of the wells R, and the well field area A:

$$\frac{Q_{CO2-total-mass}}{\rho_{CO2}} \frac{\mu_{CO2} \ln(R/r_0)}{2\pi k b (P_{CO2} - P_0)} = \frac{A}{8R^2} - \frac{\sqrt{A}}{2R} + 1 \qquad \text{(F-10)}$$

where μ_{CO2} is CO_2 viscosity at reservoir conditions (Pa s). Two times R gives the well spacing between CO_2 injectors and brine extractors. R is used with Equation F-4 to obtain the total number of CO_2 wells. The solution of Equation F-10 requires a given area A, and all of the other parameters. The area required will depend on the pore space available, how efficiently that pore space can be used to store CO_2, and the total amount of CO_2 to be stored. Thus, A is obtained by:

$$A = \frac{G_{CO2}}{b\, \phi \rho_{CO2} E} \qquad \text{(F-11)}$$

where E is the "efficiency factor," which is defined as the volume of CO_2 in the storage volume divided by the total pore space in that same volume. For the problem the analysis is interested in solving, all terms on the right hand side of Equation F-11 are known except for E. Using the numerical simulations described in Section F.2, several forecasting insights develop for E when looking to both the injection–extraction case, and the case where only injection occurs.

Once the analysis solves Equation F-11, one can, in the injection with extraction case, solve Equation F-10 for well spacing and then solve Equation F-5 for number of injection wells. Implementing the case of CO_2 injection without brine extraction begins by comparing injection rates in numerical simulations with and without brine extraction. Thus, numerical simulations are used to estimate E for both injection with extraction and injection only. Numerical simulation results are also used to "tune" the analytic well flow equation for injection with extraction (Equation F-9), and finally, numerical simulations with and without brine extraction provide a relative comparison of well flows for each case that can be used to estimate injection only flow rates once the injection extraction flow rates have been solved and tuned. These steps are explained in more detail in the next two sections.

F.2 Validation and "Tuning" of Injectivity Methods

Equation F-10 is based on several restrictive assumptions (see Section F.1). The analysis compares results from Equation F-10 to those of a numerical multiphase flow reservoir simulator to obtain "tuning factors" such that the analytical solution implemented in WECSsim will satisfactorily reproduce the numerical results. The numerical solutions are also used to find CO_2 storage efficiency factors (*E* from Equation F-11) as a function of well location relative to the well field boundary. The validation by TOUGH2-ECO2N (Pruess, 2005) requires a known domain, permeability, and porosity (and relative permeability and capillary pressure given by relations for the Mount Simon Sandstone), and a given number of wells. The analysis uses a variety of domain sizes, well spacing, and permeability-porosity combinations in TOUGH2. For a given porosity and number of wells, the analysis varied total area and permeability in order to get plume sizes that fill a large part of the domain without reaching breakthrough at the brine extraction wells (see Figure F-3), after a specified well field lifetime of 30 years. As seen in Figure F-2, the analysis was done for a wide range of porosity and permeability values in order to capture most of the range of porosity and permeability estimated for the WECSsim saline formations. The analysis was done both for open and closed boundaries to the model extent. Other given variables include the remaining parameters of Equation F-10. (Note that to achieve the approximately one-to-one volumetric injection and extraction rates mentioned in Appendix F-1, very low pressure at extraction wells in TOUGH2 was required, low enough that formation damage might be expected. Additional work has been done to evaluate extraction rates that would be associated with more realistic extraction pressures (Heath et al., 2013), but the intuitive one-to-one volumetric injection to extraction ratio is maintained for this analysis.)

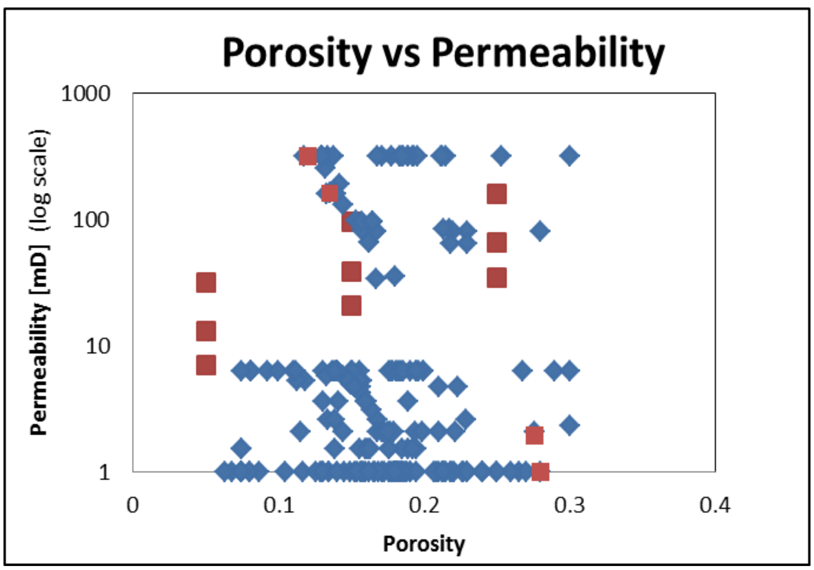

Figure F-2. Porosity-permeability parameters space for WECSsim default mean values (blue diamonds) and the TOUGH2 runs (red squares).

Note: TOUGH2 runs (red squares) were used to develop a tuning factor for the analytic well flow equation as well as estimates of local storage efficiency.

The concept of "local efficiency factors" were developed to help implement the CO_2-injection-brine-extraction injectivity methods in WECSsim on a well by well basis. The maximum local efficiency factor or $E_{local\text{-}max}$ is defined as the volume of CO_2 per void space within the plume extent, and is conceptually the maximum storage efficiency achievable in an injection-extraction regime immediately before CO_2 breakthrough to the extraction wells. Figure F-2 illustrates the square area as fitted to the maximum CO_2 plume extent for three different output times. Local efficiency, not qualified by "maximum", or E_{local} is the same calculation but for a square area with corners fixed at the extractor well locations. This area is also called the local area for the analysis presented here and is shown by the lighter yellow area of the grid refinement in Figure F-3. Maximum local efficiency is fairly constant with time but has some change at later times, probably due to the non-square shape of plumes on the corners and sides (see Figure F-4). Local efficiency versus time is linear in log-log space (see Figure F-4). Local efficiency becomes maximum local efficiency immediately before CO_2 plume breakthrough to the extraction wells. Thus, maximum local efficiency, which is relatively easy to measure because it is stable in time can be used as an upper limit of local efficiency for the CO_2-injection-brine-extraction regime.

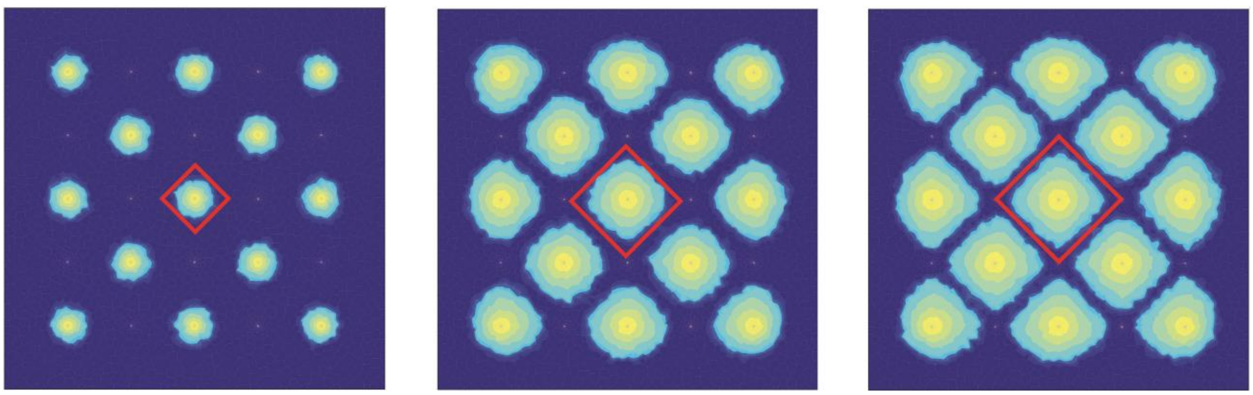

Figure F-3. CO_2 plume (shown in light blue to yellow) growth through time from TOUGH2.
Note: The red box is fitted to the maximum CO_2 plume extent (as defined by a minimum CO_2 saturation at the plume margin of 0.01). Maximum local efficiency factor is the volume of separate or free phase CO_2 (as opposed to dissolved CO_2) divided by the volume of voids associated with the red box (which grows with the plume). The third image on the right shows plume sizes at the end of the project lifetime (i.e., 30 years).

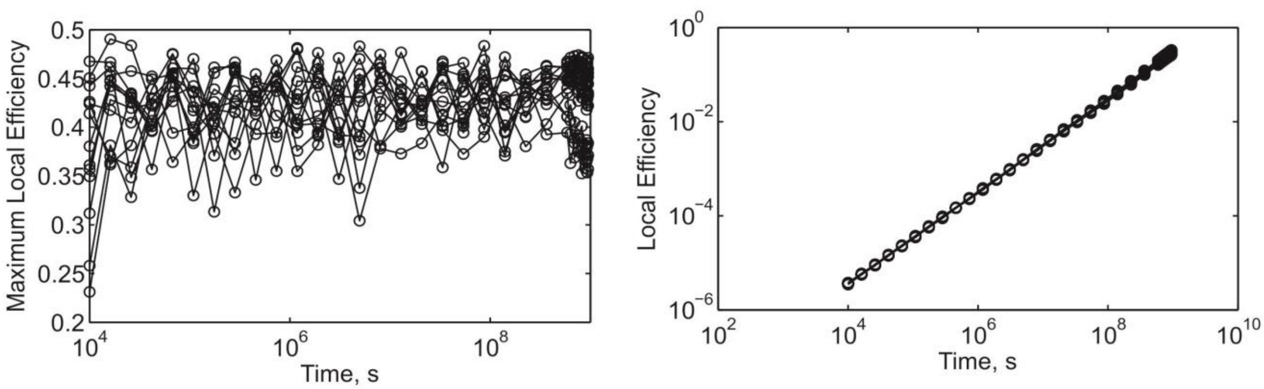

Figure F-4. Maximum local efficiency and local efficiency for 13 CO_2 wells in a total domain size of 28 km on a side.
Note: The permeability and porosity were 121 mD and 0.14, respectively. Breakthrough of CO_2 at the extraction wells never occurred.

Analysis of TOUGH2 results for CO_2 injection and storage efficiency led to a definition of seven different injection well types based on their location in the well field:

- Corner (domain edge on two sides).
- Edge (domain edge on one side).
- Interior1, Interior2, Interior3, Interior4, and Interior5+ (separated from the closest domain edge by 1,2,3,4, or 5 or more injection wells respectively (or 3, 5, 7, or 9 or more radii of influence respectively)).

These location definitions are shown visually in Figure F-5.

The TOUGH2 simulation results for CO_2 injection and storage efficiency are shown as a function of well location in Figures F-6 and F-7 respectively. The CO_2 injection results (Figure F-6) are normalized by dividing the average flow rate predicted by the analytic equation (Equation F-9) by the average flow rate over the simulation time for all wells of a certain type. This is the injection tuning factor used to modify the analytic equation results.

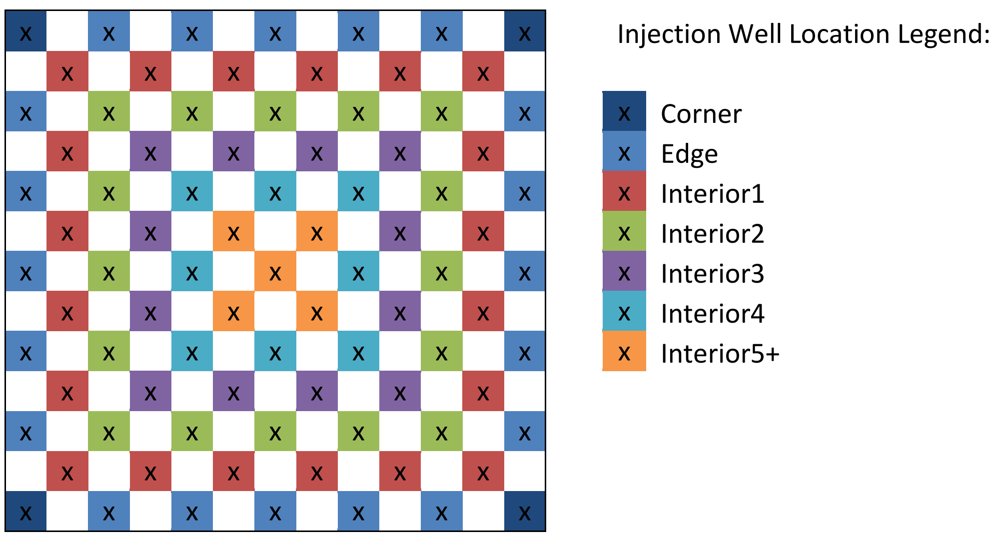

Figure F-5. Injection wells defined as a function of location with respect to the well field boundary.

The TOUGH2 simulations were for up to a 7x7 injection well field size, which does not include enough wells to represent Interior4 or Interior5+ wells. These values were extrapolated in the following manner. First, the injection ratio for the injection extraction case was the same for Interior3 wells with open and closed boundaries. Thus, this value was assumed constant for all deeper wells, and assigned to the Interior4 and Interior5+ categories. Similarly, the injection only with closed boundaries case for Interior3 wells was assumed to apply to the Interior4 and Interior5+ wells. Finally, the injection only with open boundaries case (blue line in Figure F-6) was assumed to be the same for Interior5+ wells as for Interior5+ injection only wells with closed boundaries based on visual extrapolation of the values shown in Figure F-6. Interior4 wells for the injection only with open boundaries case were found by interpolation between the Interior3 value and the Interior5+ value. These extrapolations implicitly assume that any well five or more rows into a well field will act independently of boundary conditions, and more specifically, will act like a well in a closed formation.

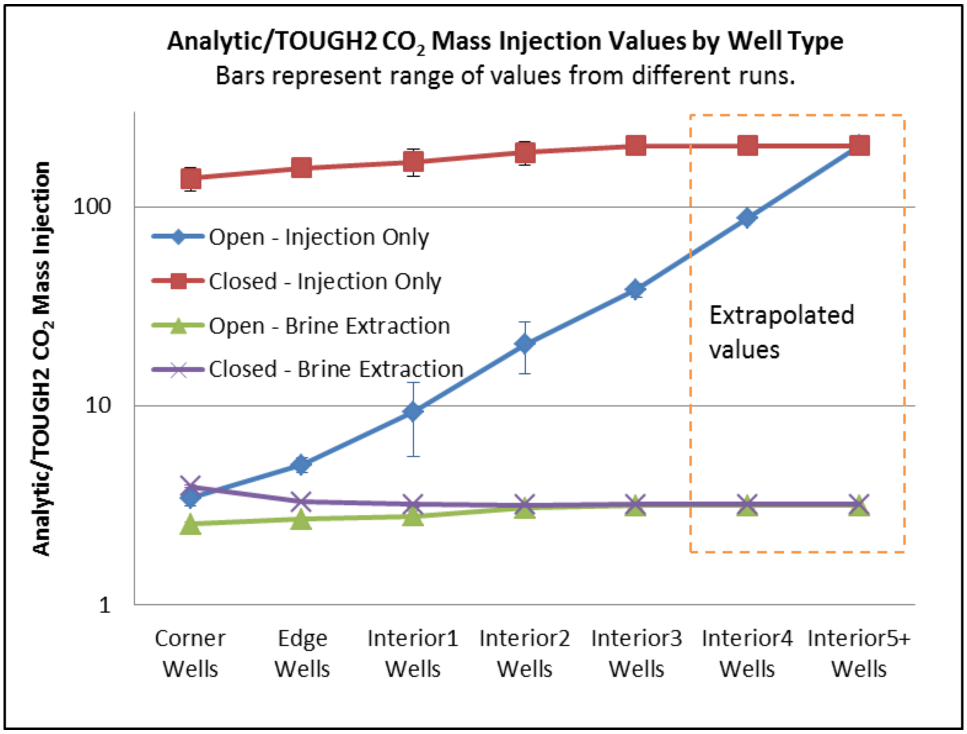

Figure F-6. The ratio of analytic injection rate to numerical injection rate as a function of well location, boundary condition, and whether or not there is simultaneous brine extraction. The boundary conditions (open or closed) don't matter for wells 5 or more injection wells away from the boundary.

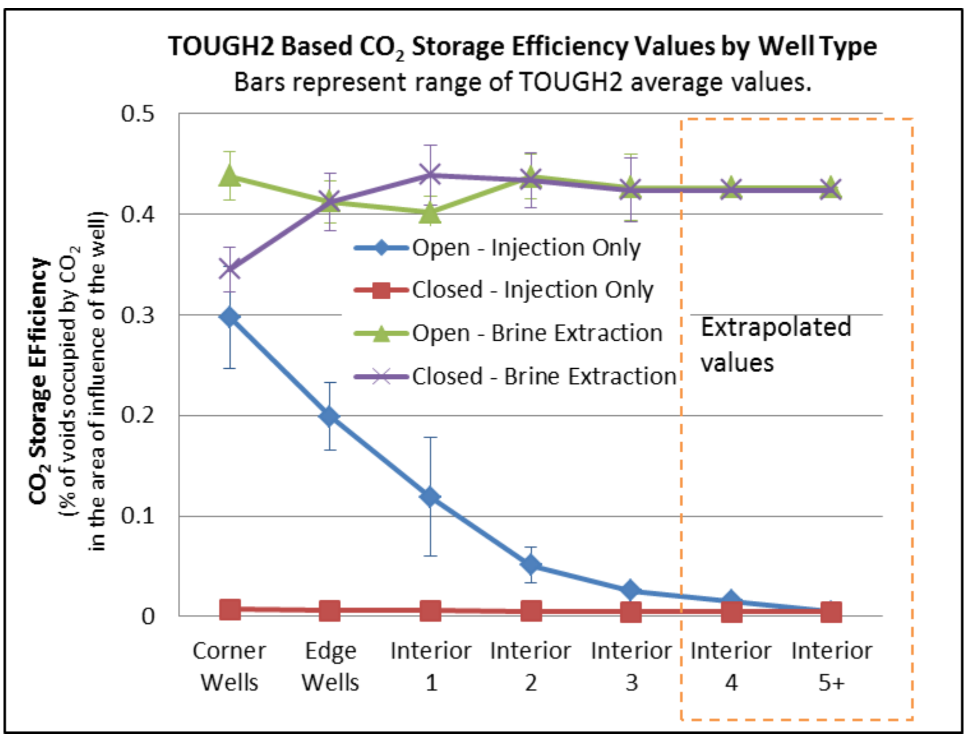

Figure F-7. Local storage efficiency for injection wells as a function of well location, boundary condition, and whether or not there is simultaneous brine extraction.

In addition to the injection rate and storage efficiency relationships shown in Figures F-6 and F-7, one other piece of information necessary to complete the WECSsim implementation was gleaned from the TOUGH2 runs. In the runs that were made for closed boundary conditions with injection only, the domain "pressured up" to the pressure imparted at the injection wells in 1.7 years after which point no additional injection occurred. This is part of the reason for the drastic difference between injected mass for the injection only regime compared to the injection extraction regime seen in Figure F-6.

F.3 Implementation of Injectivity Methods in WECSsim

For any given power plant and CO_2 capture scenario, WECSsim must select where to inject the captured CO_2. WECSsim does this by calculating how much it would cost to transport and inject the given CO_2 flux into any of the available saline formations. To estimate injection costs, WECSsim's analysis needs information on how much formation area is required, and how many injection wells are required. Porosity, thickness, and storage efficiency of injected CO_2 are used to determine the area required. Permeability, well spacing, and a variety of other formation specific properties are used to calculate injection rates and, thus, number of wells required. As described in Appendices B–E, formation area, thickness, depth, porosity, and permeability estimates are available for most formations (the appendices explain how formations with limited data were addressed). Initial pressure estimates in the formation uses formation depth by assuming a hydrostatic pressure gradient from 1 atmosphere at land surface (or sea surface for offshore formations). Initial formation temperature estimates use depth and a spatially distributed temperature gradient map (see Appendix F.5). This leaves three important and interrelated unknowns to be solved for using relationships from Appendices F.1 and F.2:

- Well spacing
- Formation injectivity
- CO_2 injection rates expected in each well

F.3.1 Well Spacing

The first step to implement the injectivity methods in WECSsim is to determine the initial well spacing. As will be seen, the well spacing is different for the injection extraction case and the injection only case. Well spacing for the injection extraction case is solved first.

Injection-extraction well spacing
The analytic injection rate for a single injection well surrounded by extraction wells is (see Equation F-9):

$$Q_a = \frac{2\pi bk\Delta P}{\mu \ ln\left(\frac{R}{r_0}\right)} \qquad \text{(F-12)}$$

where k and b are permeability of the formation to CO_2 and formation thickness, respectively (as used already), ΔP is the pressure gradient, which in this case is injection pressure less the formation initial pressure, μ is the viscosity of CO_2, R is ½ the distance between injection wells and extraction wells, and r_w is the well bore radius. This analytic flow rate is corrected to numerical flow rates observed in TOUGH2 with a tuning factor G:

$$Q = \frac{Q_a}{G} => Q = \frac{2\pi bk\Delta P}{\mu \ ln\left(\frac{R}{r_0}\right)G} \qquad \text{(F-13)}$$

These calculations are also based on the notion that right before breakthrough of CO_2 to the extraction wells, the total volume of CO_2 that has been injected, which can be defined as flow rate times time, will be equal to the area between extractor wells times the formation thickness times the porosity times the maximum storage efficiency:

$$Q * t = bA_{local}\emptyset E_{max} \ \rightarrow \ Q = \frac{bA_{local}E_{max}}{t} \qquad \text{(F-14)}$$

where t is the time of CO_2 breakthrough to the extraction wells, which for purposes here is considered the well field lifetime, A_{local} is the area between extraction wells (essentially the area in the well field associated with a single given injector), $\emptyset$ is porosity of that area, and E_{max} is the storage efficiency in that area at CO_2 breakthrough. Both R and A_{local} can be defined by the distance L between injection wells and extraction wells:

$$A_{local} = 2L^2 \qquad \text{(F-15)}$$

$$L = 2R \qquad \text{(F-16)}$$

Substituting F-15 into F-14 and F-16 into F-13, and combining:

$$\frac{b2L^2E_{max}}{t} = \frac{2\pi bk(P_{CO2} - P_0)}{\mu \ ln\left(\frac{L}{2r_0}\right)} \qquad \text{(F-17)}$$

Moving all terms with L to the left side and all other terms to the right side:

$$L^2 \ln(L/2r_w) = \frac{\pi k\Delta Pt}{\mu\emptyset E_{max}G} \qquad \text{(F-18)}$$

Equation F-18 illustrates that well spacing is a function of permeability, porosity, pressure gradient, CO_2 viscosity, well casing radius, storage efficiency, tuning factor, and the well field design lifetime–all parameters for which the analysis has estimates. The analysis solves for CO_2 viscosity based on depth, itself based on background temperature and pressure in the formation and TOUGH2 referenced lookup tables (Pruess, 2005). Maximum pressure at the well is assumed to be 90% of the formation fracture pressure which is calculated based on depth and an assumed fracture gradient of 0.65 pounds per square inch (psi) per foot of depth (based on a fracture gradient used by Schlumberger Carbon Services (SCS, 2010) in a feasibility assessment for the Mount Simon Formation in Illinois). The well pressure might be less if flow is high enough that head drop in the well bore becomes important. Well bore flow constraints and pressure considerations are discussed in Section F.3.3. The pressure gradient is the well pressure less the background pressure.

Equation F-18 solves iteratively by moving the natural log term to the right hand side, using the well spacing value from the previous iteration (L_{n-1}) in the natural log term, and solving for the current iteration well spacing (L_n) as shown in Equation F-19.

$$L_n = \left[\frac{\pi k \Delta P t}{\mu \emptyset E_{max} G \ln(L_{n-1}/2r_w)}\right]^{\frac{1}{2}} \qquad \text{(F-19)}$$

The first iteration uses an initial value of L_0 = 10 kilometers as the initial seed, though the value has almost no impact on the result (as long as it is positive and reasonable) because it is within the natural log term and it converges rapidly. WECSsim uses three iterations, and the change in L from the second iteration to the third is less than 0.15% for all formations. F-19 is used to define well spacing in each formation. As shown in Figures F-6 and F-7, the CO_2 injection ratio and maximum storage efficiency both vary as a function of well location in the well field, whether the formation is open or closed at the boundary, and whether brine is being extracted or not. For purposes of well spacing for injection with extraction, the brine extraction case with a fifth level interior well (which is independent of boundary conditions) is used.

Injection only well spacing

As mentioned in Section F.2, when TOUGH2 model configurations with closed boundaries used for the injection extraction cases were rerun with the extraction wells turned off, the formation pressure increased and injectivity was lost completely after only 1.7 years as compared to 30 years of injection with extraction wells included before the CO_2 plume was completely developed and close to breakthrough to the extraction wells. If an injection only well field with closed boundaries is to last for 30 years, 30/1.7, or 17.6 times more area would be required per injection well. This equates to increasing the well spacing for each formation for the injection and extraction case by $\sqrt{17.65} = 4.2$ times. Thus, the injection extraction well spacing calculated with Equation F-19 is multiplied by a factor of 4.2 to get well spacing for the injection only case so that the well field lifetime for all wells including Interior5+ wells is the same for injection only as for injection with extraction. By basing well spacing on Interior5+ wells, which act independently of boundary conditions, the well spacing becomes independent of boundary conditions. If the formation has an open boundary, wells besides the Interior5+ wells will be spaced somewhat inefficiently. In practice, these wells could be used for longer than their specified lifetime.

F.3.2 Well Type Distributions

Once well spacing is known, the total number of wells required to completely fill each formation is calculated as the area of the formation divided by the area associated with each well (distance between injectors squared). Next, the total number of wells in the formation is used to approximate the percentage of edge wells, and each type of interior wells. The default is to then force this ratio across all injectors into the formation. This essentially lumps the properties of the formation across all injectors, which is reasonable for most injection regimes, but requires additional discussion for two special cases.

Special case 1: Injection only into a lightly used open formation

Applying a well type percentage derived from a full formation to all wells in the formation is reasonable for injection-extraction into an open or closed formation, or injection only into a closed formation, because in these three cases the injectivity is only weakly tied to the location of the injectors (low slopes in Figure F-6). For the injection only into an open system case, it is appropriate for the situation where the formation is completely filled because the ratio of well types for the entire formation being filled is what is being applied to each individual well field in the formation. However, when the formation is not completely filled, it will underestimate the injectivity for those power plants that do actually use the formation. For example, model defaults suggest that, assuming open boundaries and injection only, it would take 1,040 injection wells 30 years to fill the Mount Simon Sandstone. Of these wells, 47% would be Interior5+, and thus unaffected by the open boundary condition. If a single power plant using the Mount Simon Sandstone only requires four injection wells however, and that plant is the only power plant to use the formation, then all injectors would be corner wells, with much better (higher) injectivity. This situation can be simulated by removing competition for sinks from the analysis, but the model weakness is that with competition, all injection is limited to the average that would occur if the formation were to be filled. This assumption improves the more a given formation is utilized. Running WECSsim in fleet analysis mode with model defaults except for specifying open boundary formations and an injection only regime suggests that over 97% of the CO_2 would be stored in only 20 formations. Thus, the majority of storage occurs in the same formations, which provides some justification to the modeling approach utilized.

Special case 2: Injection only into large closed formations, no competition

Another difficult situation to handle is a situation in which the WECSsim user wishes to simulate injection only into a relatively large formation with closed boundaries, and without competition between CO_2 producers for the storage resource. If the storage formation is large enough compared to the CO_2 to be stored, the injection formation will be effectively open from the perspective of the injection wells. To handle this case, WECSsim assigns an arbitrary threshold to formation storage below which the injection is treated as if it is into an open formation regardless of specified formation boundary conditions. Above the specified threshold, the injection is treated on a continuum between specified boundaries at full formation and open boundaries at the threshold with linear interpolation of injectivity between. By default, the threshold is 50% of formation use, meaning that if a single CO_2 producer will fill less than half of a given formation, the boundary conditions of the well field are treated as open. This special case slows down the model performance substantially because the fraction of wells of each location type must be recalculated iteratively for every power plant considered.

F.3.3 Actual injection rates

Geology controlled

If the flow rate into the formation is divided by the maximum pressure gradient, the result is an injectivity for the formation, meaning the amount of CO_2 that can be injected per unit pressure gradient.

$$I = \frac{Q_{vn}}{\Delta P} \tag{F-20}$$

Once the well spacing (which is different for injection with extraction compared to injection only) and the fraction of each well type are known, the injectivity *of each well* in the formation is solved with Equations F-13, F-16, and F-20 (which is just a rearrangement of F-13) by randomly choosing a well location (Corner, Edge, Interior1, etc.) from the distribution of well locations for the full formation. As discussed in Appendix E, each formation in WECSsim is associated with a rock type or mix of rock types and in this way assigned a distribution of porosity and permeability values. Mean values for porosity and permeability (and a deep interior well location) are used in the calculations of well spacing using Equation F-19. The rationale for this is an assumption that while developing a well field for CO_2 storage, well spacing would be decided a-priori based on average geologic properties and the most constraining well locations. However, the user is given the ability to allow stochastic variation in permeability and porosity either at the well by well level, or the well field level by selecting the appropriate option from the input switch shown in Figure F-8. The input switch for this option resides in both the Sink Porosity and Sink Permeability pages of the CO_2 Storage tab of WECSsim.

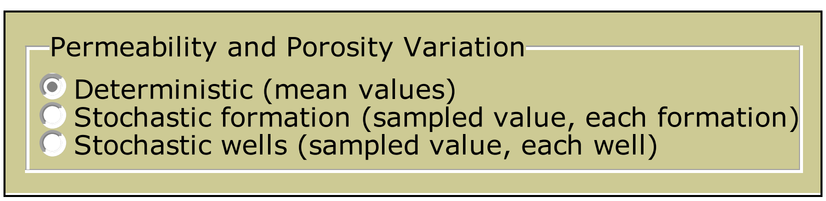

Figure F-8. Input switch allowing the WECSsim model user to change the stochastic options for porosity and permeability.

Once the injectivity value for a given well has been calculated, it is used, along with flow equations for the CO_2 flow through the well bore itself (discussed below), to solve for flow in the well. WECSsim then compares this amount to the total CO_2 flux that must be injected and repeats the process until a sufficient number of wells have been simulated.

One final point of clarification to note regarding the injection rate determined for the formation is that injection rate for the injection only case is calculated by multiplying the injectivity for the injection extraction case by the ratio of *storage efficiency* for injection only divided by the *storage efficiency* for injection extraction. This avoids directly using the injection only tuning factor, which is based on TOUGH2 runs in which injection effectively stopped 1.7 years into a 30 year run. By calculating it this way, the injection rate for the injection only case is the equivalent of the injection rate in TOUGH2 for the first 1.7 years of the run, but applied to the entire lifetime of the well field. This is conceptually reasonable because the area associated with each injection well is 30/1.7 = 17.6 times greater in the injection only case compared to the injection extraction case.

Well bore and geology controlled

Equation F-13 neglects any pressure loss in the well bore itself. As discussed previously, WECSsim limits the maximum well pressure to 90% of formation fracture pressure. The actual well pressure is developed by assuming the well head pressure is 15 MegaPascals (MPa) which is a desired pressure in CO_2 transportation pipelines (McCollum and Ogden, 2006). The background pressure in the formation is known, and so the pressure in the well at the injection depth is a pressure between the wellhead pressure and formation background pressure. This results in a flow through the well bore according to the Darcy-Weisbach equation (Munson et al., 1994) that is the same as the flow into the porous media based on the injectivity from Equation F-19. Specifically, the flow that results from simultaneous solution of both equations connected by a common well bottom pressure is found as follows:

1. WECSsim specifies a set of hypothetical well bottom pressures equally distributed between background pressure in the formation and the maximum desired well bottom pressure (90% of fracture pressure).

2. Using Equation F-13, WECSsim calculates the flow rates of CO_2 into the formation that would result from the pressure gradients associated with the specified well bottom pressures.

3. Using the Darcy-Weisbach equation, WECSsim calculates the head loss through the well bore that would be associated with these flow rates. In order to make this calculation, WECSsim must calculate the friction factor associated with each flow rate. This is done assuming an equivalent roughness of the well casing of 0.00015 feet (value for commercial steel from Table 8.1 of Munson et al. (1994)), the user-specified well radius, and the Reynolds Numbers associated with the flow rates through a pipe of that size. If the flow is laminar, (Reynolds Number less than 2,100), the friction factor is set to 64/Reynolds Number. If the flow is turbulent, WECSsim's calculations use the Serghides numerical method to estimate the friction factor (Serghides, 1984).

4. Next, WECSsim calculates the bottom hole pressures as the specified wellhead pressure plus the column pressure of CO_2 (depth*density*acceleration due to gravity), less the head losses calculated in step 3.

5. Next, WECSsim solves for the pressure where the line defined by the initial assumed well bottom pressures crosses the line defined by the bottom hole pressures calculated in step 4. If these lines do not cross, pressure will have to be reduced to prevent well bottom pressure from exceeding 90% of the fracture pressure, and well bottom pressure is set to 90% of fracture.

6. Finally, WECSsim solves Equation F-19 for the pressure gradient resulting from the well bottom pressure found in step 5. This is the average injection rate for the well. If

stochastic porosity and permeability are being used, WECSsim repeats the process for the next well, adding wells until the full flux of CO_2 from the CO_2 Capture module can be handled.

Steps 1–6, which rely on solving Equations F-14 through F-19, result in the total number of injection wells that would be required for each formation. This number, along with the depth of the wells and the total formation area required are important pieces of information that are passed to the Power Costs module. In this module, the information can be combined with additional data from other modules thereby allowing WECSsim to select the most cost effective formation to store CO_2 associated with a given power plant and CO_2 capture scenario.

F.3.4 Injection only versus injection extraction CO_2 storage regimes

From a higher level perspective, the well spacing and injectivity differences between injection only and injection with brine extraction result in a large discrepancy between the efficiency of storage resource use in the two cases. Not only does each well need almost 20 times (17.6) more area in the injection only case, the total area required for a given amount of CO_2 storage can increase by two orders of magnitude due to an efficiency factor of less than 1% for injection only compared to 45% or more for injection with brine extraction. If the total area increases on average by about 100 times larger and the area per well increases by 20 times, the number of injection wells must increase on average by about five times. Therefore, even without the extraction wells, the total required wells increases in the injection only case. On a case by case basis, the injection-only case has a lower overall cost than the injection with extraction case not because of total well numbers, but because of brine treatment costs. If injection only requires on average 5 times more injection wells, the injection rate over the well field lifetime is 5 times greater for each injection well in the injection extraction field as compared to an injection well in a well field without any extraction.

F.4 Well field Pipeline Length & Size Calculations

Once the total number of injection wells and their spacing has been calculated as described in section F.3, WECSsim calculates the length and sizes of pipelines necessary to distribute the captured CO_2 from a single pipeline to each of the injection wells. To accomplish this, WECSsim assumes the well field will be square. Additionally, it assumes that a full capacity "trunk" pipeline will run through the middle of the well field with "branch" lines with descending capacity extending laterally in both directions serving lines of wells. Figure F-9 shows the shape of any well field containing up to 49 injection wells and the pipeline sizes for the case of 49 wells.

Figure F-9. Square well field patterns for up to 49 injection wells.
Note: The well numbers are general, representing the shape the well field would take for that particular number of injection wells. The pipeline capacities in this figure are specific for 49 wells.

In this configuration, the analysis adds a segment of trunk to serve the 3^{rd}, 7^{th}, 13^{th}, 21^{st}, etc. wells[12]. Generally, a trunk segment is added whenever

$$n = \left(floor\left(\sqrt{n}\right) + 1\right)^2 - floor\left(\sqrt{n}\right) \qquad \text{(F-20)}$$

where *n* is the total number of injection wells, and *floor* rounds down to the nearest integer. Beginning with the 8^{th} well, the analysis adds branches on each side of the trunk to serve each of the next two wells after adding the trunk segment. For example, in Figure F-9, it can be seen that the 8^{th}, 9^{th}, 14^{th}, 15^{th}, 22^{nd}, 23^{rd}, etc. wells utilize new branch lines. In this way, developing a table that contains the number of segments of each size (in terms of flow rate) of pipe required for any number of injection wells becomes relatively straightforward. The length of a segment is the well spacing, and the flow rate is an integer multiple of the average injection rate, for which

[12] The trunk segment serving the 1^{st} well is considered part of the pipeline used to move the CO_2 from the power plant to the well field and is not included in the well field pipeline calculations.

the calculation of both depends on the geologic properties of the storage formation as described in Section F.3. Figure F-10 provides a graphic representation of the table used in WECSsim to determine the required number of segments of pipe of various sizes for up to 1,089 injection wells (square field with 33 x 33 wells). This is the largest field size WECSsim will develop before starting another square field. With length and flow rate, WECSsim estimates the pipeline cost using the Ogden (2002) equation for CO_2 pipelines described in Table A-5 of Appendix A.

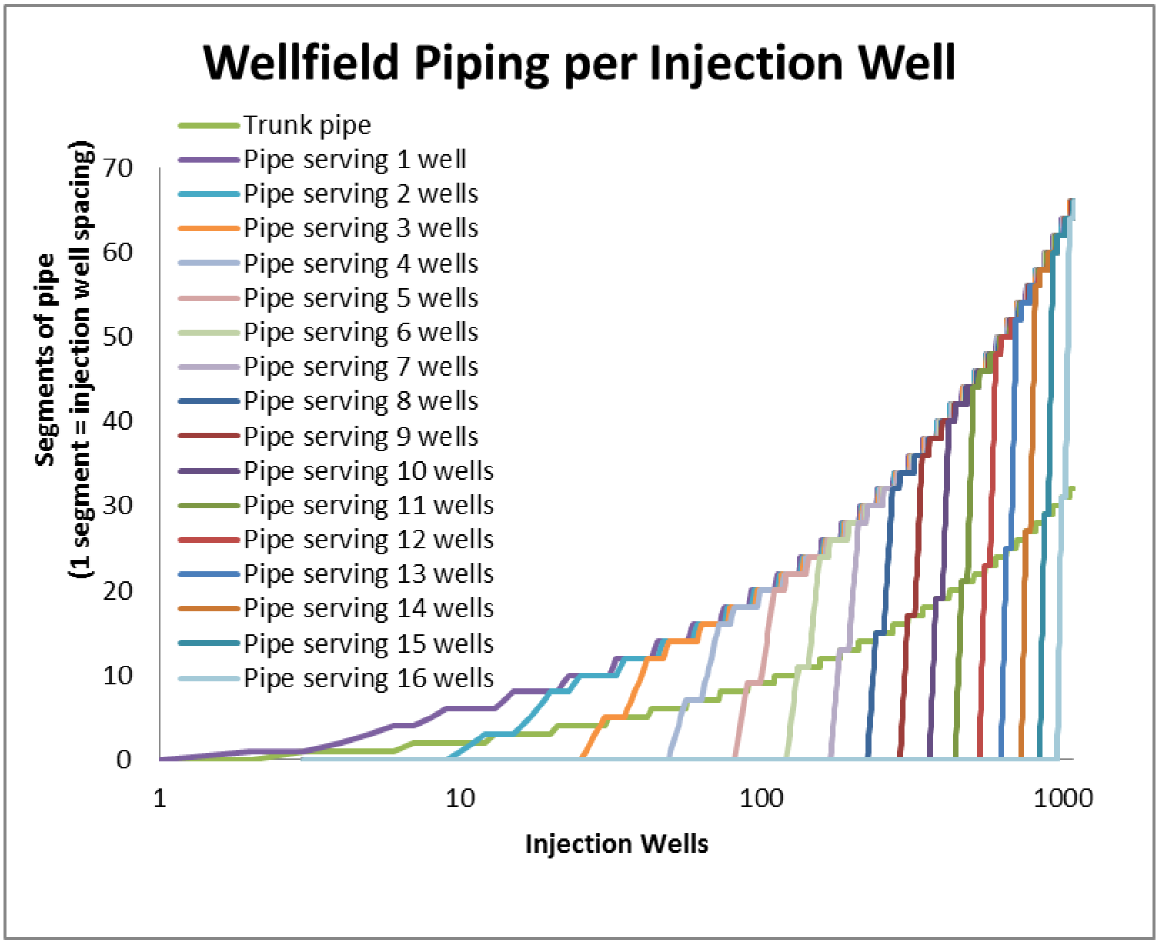

Figure F-10. Graphical representation of the lookup table used in WECSsim to calculate the length and size of pipe needed for a well field with up to 1,089 injection wells.

F.5 Geothermal Gradient Estimation for the U.S.

One of the parameters necessary for estimating what the density and viscosity of stored CO_2 would be in the subsurface is the temperature of the storage formation. There are publicly available maps of the estimated geothermal resource in North America (e.g., Blackwell and Richards, 2004); however, these maps typically represent heat flow, not just temperature at depth. The available temperature at depth maps were for depths in the range of 3.5 km to 9.5 km, which is deeper than the majority of potential storage formations evaluated in WECSsim, and the underlying data were not readily available[13]. Thus, the strategy used in the analysis was

[13] See http://www.google.org/egs/

to develop a spatial estimate of temperature gradients in the U.S. based on temperature data associated with well records (which is also the source of the geothermal resource maps).
To process the well temperature data, the following steps were taken:

1. Downloaded the Southern Methodist University Geothermal Laboratory maintained well data[14].
2. Selected all wells at least 500 meters deep, with reported thermal gradient (CO GRAD (C/km) column header), and only wells south of 49th parallel to limit to 48 states. This ended up being 380 wells.
3. Eliminated 10 wells with thermal gradients greater than 100 C/km leaving 370 remaining wells.
4. Processed these wells in ArcGIS:
   a. Added the table with these wells to ARC Map workspace with the Add Data function.
   b. Added xy data as a layer from that table using the Add XY Data tool. The location of the wells with respect to the saline formations is shown in Figure F-11.
   c. Saved the well layer as a shapefile to allow it to be selected, queried, and edited.
   d. A two dimensional surface was then created from the point well data using inverse distance weighting. The resulting spatially distributed estimate of thermal gradient is shown in Figure F-12.
   e. The visually unintuitive high gradient seen around southern South Dakota and northern Nebraska (white area in the upper Midwest shown in Figure F-12) was found to be the result of a single well, which was eliminated, and the process repeated to get the spatial distribution shown in Figure F-13. Note that none of the saline formations evaluated in WECSsim overlie the area associated with the anomalous well, so the decision to remove it did not affect the results in WECSsim.
   f. Finally, the spatial statistics of the intersection of the thermal gradient surface with the saline formations were calculated to come up with a mean, min, max, and standard deviation of estimated thermal gradients associated with each formation.

WECSsim uses the mean thermal gradient for each saline formation along with storage depth to estimate the steady state temperature of the stored CO_2. WECSsim then uses this information to calculate CO_2 density and viscosity values necessary for estimating injectivity and total CO_2 storage per area of formation.

[14] http://smu.edu/geothermal/georesou/08%20Data/SMU_heatflowdatabases9_2008.xls Accessed 9/14/2010.

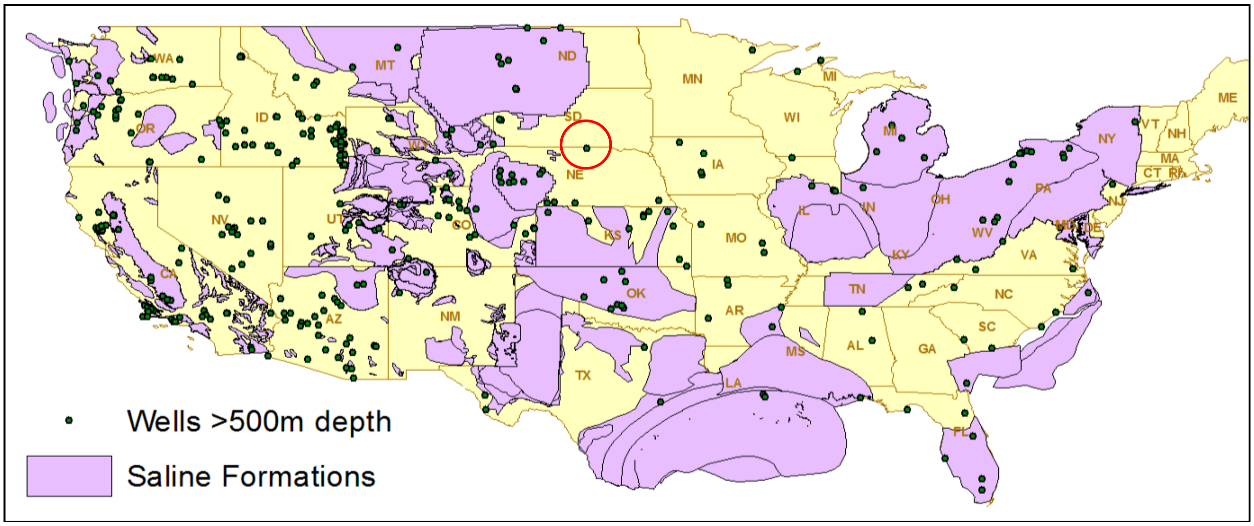

Figure F-11. Wells deeper than 500 meters with thermal gradients less than 100 degrees C per kilometer used to develop the spatially distributed estimate of thermal gradients.
Note: The well near the South Dakota Nebraska state line circled in red was eventually removed due to its high value compared to surrounding wells.

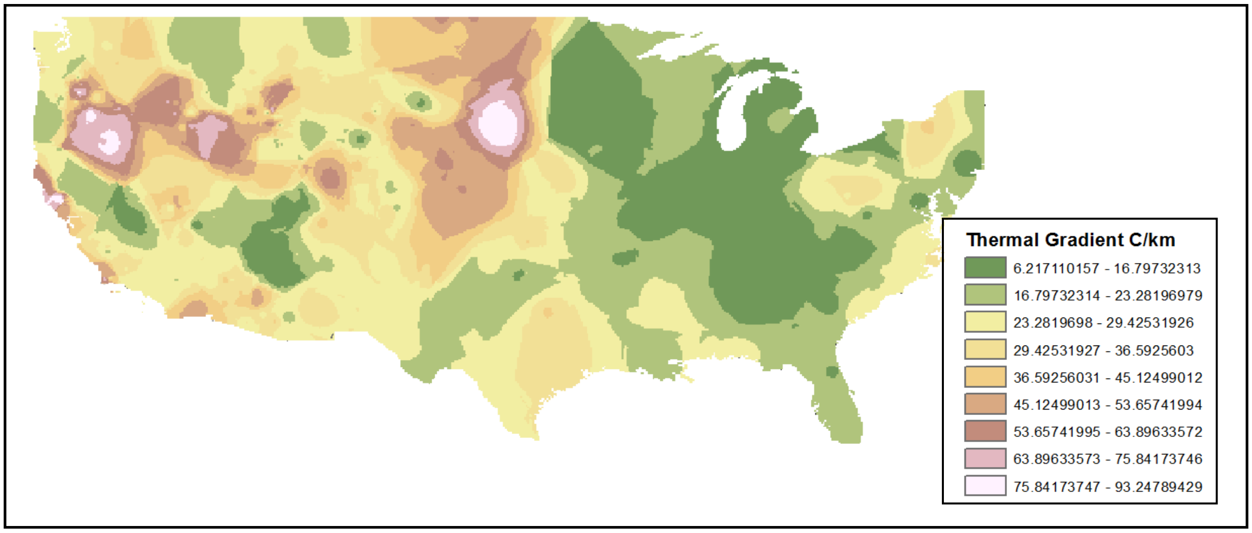

Figure F-12. Initial thermal gradient surface developed using inverse distance weighting of well based point estimates of thermal gradient from the wells shown in Figure F-11.
Note: The high gradient anomaly in the upper Midwest was a result of the single well near the Nebraska South Dakota state line circled in Figure F-11.

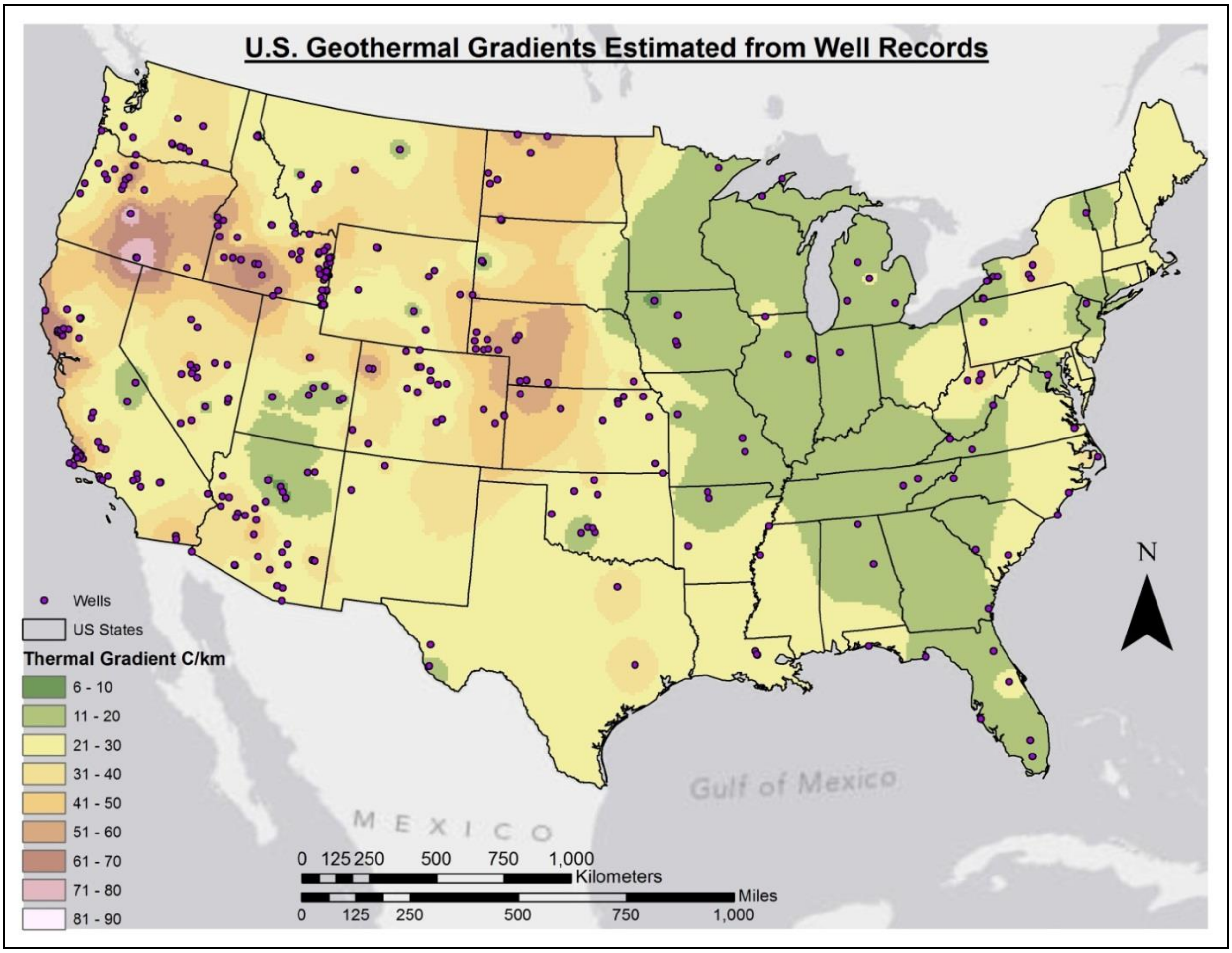

Figure F-13. Final thermal gradient surface developed using inverse distance weighting of well based point estimates of thermal gradient.

APPENDIX G: RUNNING THE MODEL

System requirements: Microsoft Windows XP or 7

Starting the Model and running a Base case:
1. INSTALL the free player from PowerSim. The Studio 7 Player is required to run the WECSsim model.
2. OPEN the PowerSim Studio model file using the Studio 7 Player.
3. ACCEPT the license agreement to use the WECSsim software.
4. NAVIGATE through the WECSsim interface to the desired screens and scenarios.

G.1 Model Navigation

The Studio Presentation mode works much like a web interface. There are Home and Back buttons for screen navigation. There are controls to run (play) the model, a single step (advance simulation one step) option to run the model, and return a model to the start (reset simulation).

MAIN INTERFACE – Click on desired model section
- Evaluate a single power plant
- Evaluate U.S. coal-fired power plants
- Evaluate U.S. coal-and-gas-fired power plants

HYPERLINK – Scrolling over words, boxes or icons on the screen that are hyperlinked will trigger a selection icon (see the information icon in Figure G-1). Click to be sent to the hyperlinked screen.

Carbon Capture Module Inputs Summary

Plant Type	PC-Sub
% Base CO2 Captured (CC)	90 %
Water withdrawal demand specific to CC & compression	298 gal/tonne CC
Make-up Power (MUP) Plant Type	PC-Sub
MUP CO2 Production Rate	1,900 lbs/MWh
% MUP CO2 Captured	90 %
MUP LCOE	13 cents/kWh
MUP Plant Cooling Type	Cooling pond
MUP water withdrawal rate	227 MGD

Figure G-1. An example of blue text that permits changes to model input values.

DATA ENTRY - Certain text in blue can be changed as needed (see Figures G-1 and G-2). Pick lists provide a fixed set of options as needed (see Figure G-2).

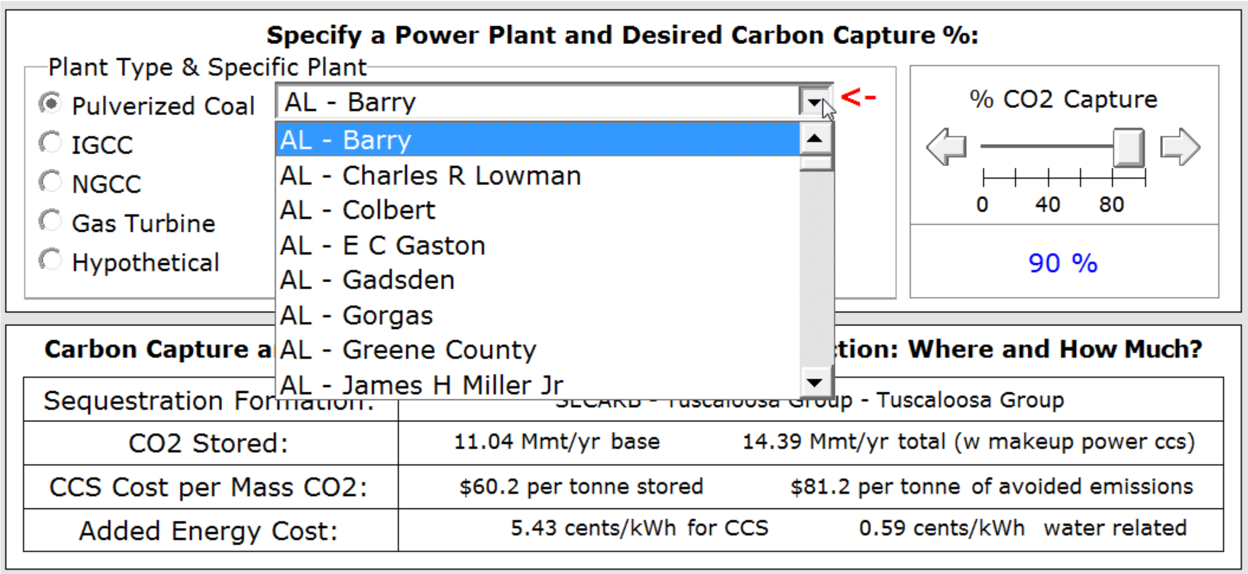

Figure G-2. An example of a pick list for Pulverized Coal power plants.

G.2 Model Navigation and Operation

HOME	Click to return to the initial WECSsim screen.
BACK	Click to return to previously visited screen.
FORWARD	Click to move forward in the list of screens previously visited.
PLAY	Click to start model simulation or click during simulation to stop.
REWIND	Click to reset simulation.
PLAY/PAUSE	Click to advance the model one step.
PERMANENT VARIABLES	Click on the downward-facing arrow to see the drop-down menu. Choose the ‘restore permanent variables’ if the model user changed any of the default assumptions to return to the base case assumption settings.
MODULE INPUT	*Overview* Click on the *italicized* model input options within each tab page to view additional module-specific options.

Distribution:

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