PARAMETRIC ANALYSIS OF TECHNOLOGY AND SYSTEMS TRADEOFFS FOR CO2 STORAGE IN SALINE FORMATIONS

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Abstract

Over the last decade, a substantial amount of economic, engineering, and geoscience research has focused on storing CO2 in geological formations. Amongst the options for geological storage of CO2 to mitigate atmospheric emissions from power plants, which include depleted oil and gas formations, unminable coal seams, and other geological systems, saline formation storage represents the largest storage potential (Litynski et al., 2008). Fossil fuel-based power plants in the U.S. (coal and natural gas) represented approximately 40% of all CO2 emissions in 2008 and therefore represent an important factor to address atmospheric CO2 emissions.

The purpose of the analysis presented here is to broadly demonstrate the sensitivity of CO2 capture and storage (CCS) costs in saline formations to changes in the water demands associated with implementation of CCS across the power plant fleet (coal and natural gas) due to parasitic energy requirements, and also discuss the effects of competition for sink space. This paper also highlights the sensitivities of the levelized cost of electricity (LCOE) to parameters in the Water, Energy and Carbon Sequestration Simulation Model (WECSsim©). This lays the groundwork for future parametric statistics-based reporting using distributions regarding the type and scale of uncertainty bounds for both performance and cost characteristics of the complete system. The national-scale version of WECSsim© developed collaboratively at Sandia National Laboratories (SNL) with the National Energy Technology Laboratory (NETL) presents the cost uncertainties involved with scaling up CCS at the national level while accounting for the substantial uncertainty associated with specific geological parameters, efficiencies of capturing CO2, and treating extracted saline water for potential cooling at power plants. The initial findings indicate under certain conditions, the majority of added cooling water demands for CCS can be met by extracting and treating saline formation waters. Additionally, the capture and compression of CO2 remains the largest share of the added costs to CCS systems as reported in Kobos et al. 2011, and that, competition for geologically-favorable storage sites will increase the costs to store CO2 due to a mild scarcity effect for these sites relative to less favorable ones with more challenging water treatment and geological characteristics (Roach et al., 2010, 2012; Kobos et al., 2012).

Methods

The WECSsim© model builds upon the Environmental Protection Agency’s (EPA) national power plant database and a saline water-bearing formations database developed by the National Energy Technology Laboratory (EPA, 2007; NatCarb, 2008). WECSsim© is a national-scale integrated assessment model, which includes interconnected modules specific to Power Plants, CO2 capture technologies, CO2 Storage in Saline Formations, Extracted and Treated Water, and Power Costs. WECSsim© can be used to evaluate a single hypothetical power plant specified by the user, a single existing power plant in the U.S., or the entire 2005 U.S. fleet of coal- and gas-fired power plants. Extracting saline water from the target saline storage formation may be an important strategy to make more efficient use of the pore space and manage pressure build up in the reservoir. A parametric scenario analysis framework identifies the key variables that may enhance the viability from a performance and cost perspective across the U.S. The St. Peter Sandstone formation (St. Peter SS), for example, could store a sizable amount of the nation’s CO2 emissions due to its large size and strategic location.

The overarching scheme of the WECSsim© model’s framework develops in a progressive manner. As described in several previous reports (Kobos, et al., 2011, 2012, Heath et al., 2012, Klise et al., 2013), each topical component receives its own module for direct connection to the literature-based assumptions, as well as customizable options.

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Figure 1 illustrates how the model develops for a single power plant and can be extracted to the full coal and natural gas-fired power generating fleet (Klise et al., 2013).

Figure 1. Illustration of the WECSim® interrelated modules that include CO₂ capture, injection, and water extraction and reverse osmosis (RO) treatment systems. While only a single power plant, CO₂ injection and water extraction well are shown, there may be many wells associated with a single plant depending upon the scale of the power plant and mass of CO₂ to be stored. (Adapted from Klise et al., 2013).

One of the core challenges to develop and refine a model such as this is capturing the salient technology-based ‘bottom-up’ components while maintaining a model with high-level results to address future infrastructure evolution questions. These questions include, ‘What are the primary cost drivers at the power plant level? Are these factors region-specific? If region-specific constraints affect the performance and economic performance of CCS systems, to what level might these technologies scale up at the national level to reduce CO₂ emissions?’

Figure 2 illustrates the current WECSim® model’s components that capture this salient technology-specific detail (power plants, specific geological formation parameters, water treatment and well technologies, etc.) while also developing the national-level results.
Cost and Performance Drivers

Extracting saline waters while storing CO$_2$ in these geologic saline formations serves two purposes. First, it decreases the water requirement loads on surface water supplies to cool the make-up power plant, and second it develops a vastly larger storage resource for the CO$_2$ by managing pressure and space within the formation(s).

Within this combined CCS and water extraction system are a few key cost and performance drivers. Developing a sensitivity analysis for a single power plant to storage sink site illustrates these drivers. The San Juan Generating Station (SJGS) acts as a case study power plant in part because of the use of this plant in previous regional analysis (Kobos et al., 2011). The cost of CCS on coal-fired power plants largely is a function of the plant’s technology, size, and percent CO$_2$ reduction goals. The capture, transportation and storage capital costs are dominated by the capture component. This is due to the substantial amount of energy required to power the capture technologies, in many cases an amine-based solvent. Figure 3 illustrates the power cost results for the SJGS base case for both CO$_2$ captured and avoided. The latter results also include the parasitic power and its additional CO$_2$ make up requirements to capture, compress and transport the CO$_2$ from the SJGS to the saline formation (in this case the San Juan - Entrada formation).\(^1\)

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\(^1\) Additional results include: four CO$_2$ injection wells required, spaced 5.5 miles apart; four saline formation water extraction wells with an average of 20 ppt TDS; total treated water cost of $25.32 per 1000 gallons; less than one mile distance between the San Juan Generating Station and the formation site; formation depth of 6,997 ft., 420 ft. thickness, and formation longevity that may last for 13,790 years if only storing CO$_2$ from this power plant.
Figure 3. Power, CO\textsubscript{2} and component-specific costs for the San Juan Generating Station to the San Juan - Entrada formation for both CO\textsubscript{2} captured (a) and avoided (reduced) (b). Note the substantial difference between the CO\textsubscript{2} Capture and Compression (CCC) costs for CO\textsubscript{2} captured vs. avoided. These correspond to a CCS cost of $61/tonne CO\textsubscript{2} for (a.) and $80/tonne CO\textsubscript{2} for (b.). ($US 2013).

Building from this representative case, three central cost and performance drivers were adjusted to illustrate the WECSsim\textsuperscript{©} model’s parameter sensitivities to the overarching results.

First, the base case for 90% CO\textsubscript{2} captured from the base plant (SJGS in this instance) was adjusted to 70% and 50%. The resulting effects on the top 15 metrics from the model are given in Figures 4 and 5. Figure 5 is an expansion of those results reported in cents/kWh in $US 2013 to more directly address how system performance characteristics affect costs on several system sub components.
Figure 4. Varying the percentage of CO$_2$ captured at the base plant (San Juan Generating Station) from 90% (base case) to 70% and then 50%.

Figure 5. Expanding select results from Figure 4 reporting in cents/kWh. Note the relatively large effects on H$_2$O extraction well costs and brine disposal costs to the other metrics. However, Figure 4 illustrates that the Make-up Power LCOE and CO$_2$ capture and compression (CCC) Costs for Amine Scrubbing have much larger absolute variations.
Second, the parasitic energy required to capture, compress, and inject CO₂ from the base power plant was adjusted to represent increasing technological efficiency. The base case is a 30% parasitic energy load for the base power plant. Two subsequent runs were developed to illustrate a lower 20% and 10% overall parasitic energy load. A key driver of new CO₂ capture systems will be an increased energy efficiency of capture. Figure 6 and 7 illustrate these parameter scenarios.

Figure 6. Varying the parasitic energy load at the base plant (San Juan Generating Station) from 30% (base case) to 20% and then 10%.
Third, the efficiency of the reverse osmosis system was adjusted to reflect both an improvement in the technology and a representative decrease in efficiency for other reasons (e.g., if local water quality chemistry results in decreased efficiency – this bounds the analysis to a high, low, and medium range to assess the sensitivity of the metrics to this key technology). Figures 8 and 9 illustrate the parameter adjustments and resulting findings.
Figure 8. Varying the ROSA Efficiency from 64% (base case) to 54% and then 74%.

Figure 9. Expanding select results from Figure 8 reporting in cents/kWh. Note the relatively (and absolutely) small effects on the majority of the metrics in both figures except for the brine disposal costs. These costs, however, represent a small fraction of the overall systems’ costs.
A key finding from this sensitivity analysis is that the LCOE is most sensitive to adjusting the percentage of CO₂ captured from the base plant, less sensitive to the parasitic energy required for the CCS systems, and least sensitive to the water treatment technology efficiency. Thus, if one were to look to reduce the overall system’s costs the most with limited research, development and demonstration (RD&D) funds, it would be advised to first determine the target percent CO₂ capture level desired, and then work to reduce the CO₂ capture, compression and transportation costs the most via reducing parasitic energy loads.

These findings also highlight the functionality of the WECSsim© model to address single power plant parametric scenarios, as well as the key technological performance and cost sensitivities to changes in technological efficiency.

**National-Scale CO₂ and H₂O Results**

Complementing the power-plant level sensitivity analyses are the WECSsim©-based national-level CO₂, water and formation use results. As Kobos et al. 2012 showed, a large number of scenario analyses can lead to a robust portfolio of parametric analyses to find out what the key drivers are when looking to minimize CO₂ emissions, water use, costs, and other salient parameters. Figure 10 illustrates a screenshot from WECSsim© for the base case where all coal and natural gas-fired power plants capture 90% of their initial CO₂ emissions while competing for the highest-performing geological saline formations available to them.

![Figure 10. The national cost curve for CO₂ capture and storage (CCS).](image-url)
Many of the larger formations that are relatively close to the power plants with favorable geological parameters (e.g., high permeability, depths that are favorable to reduce drilling costs, water salinities that are within the higher performing range of the reverse osmosis water treatment systems, etc.) comprise a large portion of the preferred low-cost CO₂ storage volumes required for the power plants under consideration. These represent the bulk of the targets implicit in the supply curves shown in Figure 10 matched with coal-fired power plants (generally far lower cost per tonne avoided CO₂ than natural gas) on the left hand half of the curves. Figure 11 illustrates the added national-scale water demands associated with CCS systems across the entire coal and natural gas-fired power plant fleet in competition for the viable saline formations to store CO₂ (the saline formations represent those at least 2,500 ft. deep and with a TDS of between 10 and 35 ppt.)

Figure 11. The national-scale water demands due to CO₂ capture and storage when reducing CO₂ emissions (base case is 90% capture of the CO₂ from the base plant, as well as the parasitic energy plant).
Figure 12 illustrates the general scale of the power plants capturing CO\textsubscript{2} and the saline formation storage formations under consideration.

Figure 12. The national-level results for the base case, assuming competition between power plants for the preferred storage locations in saline formations for CO\textsubscript{2} capture and storage (upper map, 0 – 20+ CO\textsubscript{2} capture rate (Mmt/yr); lower map, 0 – 800+ CO\textsubscript{2} storage rates (Mmt/yr)).

Figure 13 illustrates the top five saline formations in terms of their ability to store CO\textsubscript{2} from a national network of power plants looking to store CO\textsubscript{2} with the lowest cost. There may be instances where a power plant has other saline formations closer to it, but the overall systems’ cost may be lower to transport and store CO\textsubscript{2} in a formation much further away with more favorable geological performance characteristics (Kobos et al., 2012).
Discussions

Previous analyses have shown that CO₂ capture costs represent the dominant cost in a CCS cost breakdown and how there is substantial cost variability with changes to geological parameters (Klise, et al., 2013; Roach et al., 2010, 2012; Heath et al., 2012; Kobos et al., 2011, 2012; Tidwell et al., 2011). This paper expands upon the core findings presented in Klise et al. (2013) and Kobos et al. (2012) by varying the influence of core cost and performance drivers for power plants to match with the ‘most viable’ storage space in saline formations. An initial analysis of a few parameters illustrates the relative effects of CCS technology and water extraction and treatment parameters on the overall system’s costs relative to the effects of competition. An example scenario where a large coal-fired power plant (San Juan Generating Station) stores its CO₂ in a very close formation gives insight into several cost and performance sensitivities. This is just one example of the different parametric scenario analyses that can be performed by WECSsim®.

At the national level, CO₂ capture and storage technologies may revolutionize the CO₂ management portfolio amongst fuel types – principally coal and natural gas technologies. On the one hand, CCS promises to reduce CO₂ emissions from coal-fired power plant dramatically, but at a substantial cost penalty relative to the baseline. However, when taking into account the infrastructure that may be required to replace many coal-fired power plants with natural gas plants a more in-depth analysis will be something to explore further. On the other hand, CCS may provide from an engineering perspective, a manageable solution at the surface from the engineered CCS system (e.g., equipment costs are understood reasonably well up to a point, but substantial uncertainty exists in the subsurface geological formation’s performance characteristics (Herzog, 2011). The Midwest, for example, has a large portion of the country’s coal-fired power plants as well as attractive (from an economic and performance perspective) set of saline formations.
Conclusions

These initial findings suggest that a sizable portion of the performance and cost characteristics are not as sensitive as is the percentage of CO$_2$ that each power plant could capture to store in a given formation. Substantial effort has been expended to enhance the geological database presented in NATCARB to assure a reasonable set of assumptions underlie the geological parameters used throughout the WECSsim© analysis. This, combined with WECSsim©’s unique ability to incorporate competition by the U.S. fleet of coal and natural gas power plants for the national set of potential saline storage formations allow the analysis to dynamically develop CCS scenarios at both the single plant and national levels. The overarching impact of such a model is to allow interested parties to evaluate both their site-specific potential pilot cases of CCS, and to understand how their case fits within the nation’s infrastructure. Additionally, WECSsim© allows users to scale CCS up within a given region due to favorable geology, and across the grid for potential medium to large-scale deployment of these technologies. Understanding which site may compete well given their power plant and geologic sink characteristics will also be key to more accurately identify potential ‘winners’ and ‘losers’ from an engineering performance and system’s cost perspective before committing additional resources to these novel, yet relatively costly pilot and technology demonstration projects.

References

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