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The Value of Bulk Energy Storage in Sedimentary Basin Geothermal Resources for Reducing CO_2 Emissions

Jonathan D. Ogland-Hand[1], Jeffrey M. Bielicki[1,2,3], and Thomas A. Buscheck[4]

[1]Environmental Science Graduate Program, The Ohio State University; [2]Department of Civil, Environmental, and Geodetic Engineering The Ohio State University; [3]John Glenn College of Public Affairs, The Ohio State University; [4]Lawrence Livermore National Laboratory, Livermore, CA

483b Hitchcock Hall, 2070 Neil Ave., Columbus, OH, 43210

bielicki.2@osu.edu

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1. ABSTRACT

We present an approach that estimates the value that bulk energy storage (BES) in sedimentary basin geothermal resources could have for reducing carbon dioxide (CO_2) emissions from regional electricity systems. BES can be used to time-shift electricity that is generated from wind and solar resources in excess of demand to times when that electricity is needed. BES can indirectly reduce CO_2 emissions if this time-shifted electricity displaces generation from power plants that emit CO_2 (e.g., coal, natural gas). If CO_2 is used as the medium for energy storage, where excess electricity is used to compress and inject CO_2 into sedimentary basins, this CO_2-BES approach can directly reduce CO_2 emissions if the CO_2 has been captured from power plants. This stored, pressurized, and geothermally-heated CO_2 can be produced to the surface, where the energy is converted to electricity in a CO_2-Geothermal power plant. As such, CO_2-BES can directly reduce CO_2 emissions by sequestering them in the subsurface and indirectly reduce CO_2 emissions by displacing electricity that is generated from fossil fuels with time-shifted electricity that was generated by renewable energy technologies. We developed an optimization approach to estimate the indirect CO_2 emission reductions that can occur by using CO_2-BES for various prices on CO_2. The direct CO_2 emission reductions are calculated using CO_2-BES operational parameters. Our results indicate that the direct value to CO_2 is more than twice the indirect value to CO_2. Thus, this study suggests that BES in sedimentary basin geothermal resources is a far more effective approach to reducing CO_2 emissions from the electricity system than conventional BES approaches.

2. INTRODUCTION

Reducing the amount of carbon dioxide (CO_2) that is emitted to the atmosphere from the electricity system is a primary focus of climate change mitigation efforts, in part because CO_2 emissions from the electricity sector comprise a major share of the overall emissions. For example, the electricity sector was responsible for approximately one-third of the total CO_2 emissions in the United States in 2013 (EPA 2014b). One solution to this problem involves displacing electricity that is generated from conventional fossil-fueled power plants (e.g., coal, natural gas) with electricity generated by renewable energy technologies with little or no operational CO_2 emissions. But the dominant sources of renewable energy that are used to generate electricity—namely wind and sunlight—are variable, which limits the extent to which electricity that is generated from these technologies can be relied upon to satisfy demand. Bulk Energy Storage (BES) technologies can compensate for this variability by storing excess electricity and dispatching it when needed. As a result, BES can enable an increased utilization of the installed capacity of renewable energy technologies by time-shifting and dispatching electricity that would otherwise be curtailed. This time-shifting can indirectly reduce CO_2 emissions if the time-shifted electricity displaces electricity that is generated by fossil-fuel power plants. Emerging approaches to BES investigate how sedimentary basin geothermal resources could be used for energy storage. One option, CO_2-BES, uses CO_2 that would otherwise be emitted to the atmosphere as the energy storage medium in the subsurface and also extracts heat from the geothermal resource (Buscheck et al. 2016). This direct sequestration of CO_2 by the CO_2-BES system has a value to the overall effort to reduce CO_2 emissions, and the use of this sequestered CO_2 to displace CO_2-intensive electricity with electricity that has less CO_2 emissions associated with it, adds an indirect value to this effort.

In this paper, we estimated the value of the direct and indirect reductions in CO_2 emissions from CO_2-BES for a hypothetical case study that uses the electricity generation and demand profiles for a day in the Electricity Reliability Council of Texas (ERCOT) electricity system. ERCOT was chosen as a case study for this analysis because the state of Texas has substantial wind and sedimentary basin resources. Sections 3 and 4 present the approaches used to calculate the indirect and direct reductions in CO_2 emissions associated with CO_2-BES, respectively. Section 5 presents our method to determine value of CO_2-BES using those direct and indirect reductions in CO_2 emissions.

3. INDIRECT REDUCTIONS OF CO_2 EMISSIONS FROM CO_2-BES

There are three major types of power plants: (1) base-load power plants produce electricity at a relatively constant rate to meet the portion of electricity demand that is constant, (2) intermediate-load power plants can respond to changes in demand and generate electricity to meet the portion of electricity demand that fluctuates, and (3) peak-load power plants are used most often in the summer to generate electricity to meet the peak demand from air-conditioning (Denholm & Hand 2011). Base-load power plants (e.g., coal and nuclear) tend to generate electricity more cheaply than intermediate and/or peak-load power plants (Masters 2004), but the relatively constant output of these power plants constrains the flexibility of the electricity system. Since base-load power plants cannot easily adjust their electricity output in response to fast changes in electricity demand or generation elsewhere in the system, these base-load power plants cannot accommodate electricity that is generated by variable wind and solar energy technologies. As a consequence, when the sum of electricity that is generated from renewable resources and the amount of electricity that is generated from base-load power plants is greater than demand, the electricity generated by renewable energy technologies must be curtailed to ensure stability in the electricity system. In this way, the inability of base-load power plants to quickly ramp and accommodate fluctuations in electricity demand and electricity supply can constrain the utilization of renewable electricity technologies in the electricity system. Bulk energy storage technologies like CO_2-BES, pumped hydroelectric energy storage (PHES), or compressed air energy storage (CAES) can reduce this constraint by storing the electricity that would otherwise be curtailed and time-shifting it to a time when less electricity is being produced by renewable energy technologies and/or there is greater demand for electricity. To estimate the indirect CO_2 emission reductions that can occur with this time-shifting, we developed a linear optimization program to represent the operation of the ERCOT electricity system.

3.1 Data

The Electricity Reliability Council of Texas (ERCOT) produces 60-Day Security Constrained Economic Dispatch (SCED) Disclosure Reports that provide (1) the amount of electricity that was generated for fifteen-minute intervals for every ERCOT electricity generation unit (EGU), and (2) the generation type of each EGU (ERCOT 2015). There are a limited number of 60-Day SCED Disclosure Reports available online and we used the report from October 2, 2015 for this study. Based off the data, we grouped the electricity system into four components: nuclear, coal, natural gas, and wind. Table 1 shows the total diurnal amount of electricity generated and the corresponding electricity system components for each EGU type. As a further simplification, the hydro, other renewable, and other categories were not included in a component because they only accounted for 0.55% of the total amount of electricity generated.

Table 1: Type of generator as defined by ERCOT and corresponding electricity system component classification

Type of Generator	Percent of Total Daily Generation	Electricity System Component
Combined Cycle (capacity greater than 90MW)	36.77%	Natural Gas
Combined Cycle (capacity less than or equal to 90MW)	1.35%	Natural Gas
Coal, Lignite	31.56%	Coal
Dynamically Scheduled Generation	0.03%	Natural Gas
Gas Steam Non-Reheat Boiler	0.00%	Natural Gas
Gas Steam Reheat Boiler	0.08%	Natural Gas
Gas Steam Super Critical Boiler	0.46%	Natural Gas
Hydro	0.08%	N/A
Nuclear	13.18%	Nuclear
Other renewable	0.15%	N/A
Simple Cycle (capacity greater than 90MW)	4.30%	Natural Gas
Simple Cycle (capacity less than or equal to 90MW)	1.08%	Natural Gas
Wind	10.62%	Wind
Other	0.32%	N/A

We estimated the capacities of each electricity system component by summing the maximum amount of electricity that was generated over the entire day by all EGUs in each category. Similarly, electricity demand was defined as the total amount of electricity that was generated by all EGUs and the amount of electricity generated by wind energy technologies available for dispatch was defined as the amount of electricity generated by wind energy technologies. We assumed that the ramp rates for nuclear and coal-fired base load power plants were zero, meaning that base-load power plants are constrained to generate the same amount of electricity regardless of demand. The ramp rate for the natural gas component was calculated as the largest change between consecutive time intervals for the sum of all of the natural gas EGUs and we assume that 10% of natural gas component capacity must be used at all times during the day. Lastly, the generation of electricity from CO_2-BES is not constrained by a ramp rate because the thermophysical properties of CO_2 reduces the need for submersible pumps (Buscheck et al. 2016).

The variable cost of electricity production and CO_2 emission rates for all five electricity system components were taken from a Congressional Research Service (CRS) Report and Environmental Protection Agency (EPA), respectively (Kaplan 2008; EPA 2014a). The variable cost of geothermal power plants was used for CO_2-BES.

Figure 1 and Table 2 show the electricity demand and amount of electricity generated by wind energy technologies available for dispatch, and the relevant electricity system component information that is used in the linear program, respectively. In other words, Figure 1 and Table 2 show the inputs to the linear program.

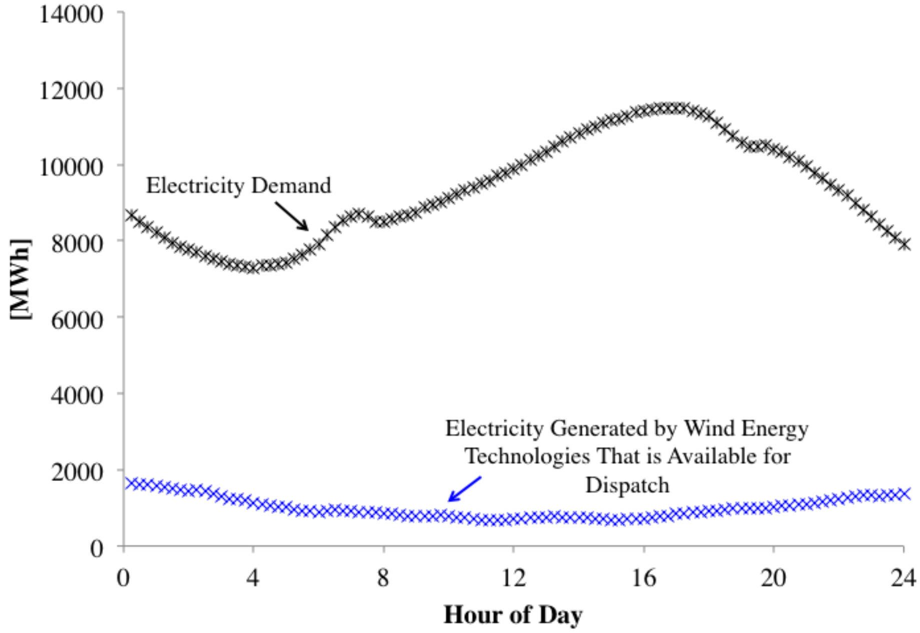

Figure 1. The amount of electricity that was generated by wind energy technologies available for dispatch and the electricity demand on October 2, 2015.

Table 2. Information used in the linear program for each electricity system component

Electricity System Component	Capacity [MWh]	Ramp Rate [MWh]	Variable Cost [$/MWh]	CO_2 Emission Rate [tCO_2/MWh]
Nuclear	1,240	0	8.23	0.00
Coal	3,644	0	17.31	0.91
Natural Gas	5,921	1,386	33.27	0.45
Wind	N/A	N/A	6.67	0.00
CO_2-BES	58,350	N/A	13.69	0.00

3.2 Linear Optimization Program

The linear optimization program minimizes the cost of generating electricity to meet the daily demand for electricity with a price on CO_2 emissions. Using the linear program, we investigated two scenarios in this hypothetical case study to determine the indirect reductions in CO_2 emissions associated with CO_2-BES. In Scenario A, the optimization model determines the cost-minimized electricity generation from (1) the nuclear component, (2) the coal component, (3) the natural gas component, (4) the wind energy technology component, and (5) the CO_2-BES component for an exogenous demand. The same process is used in Scenario B except the CO_2-BES component is removed. In both scenarios, the CO_2 emissions associated with each price on CO_2 are calculated using the emission rates shown in Table 2. Figure 2 shows the overall process. The indirect reductions in CO_2 emissions are defined as the difference in CO_2 emissions between Scenario A and Scenario B.

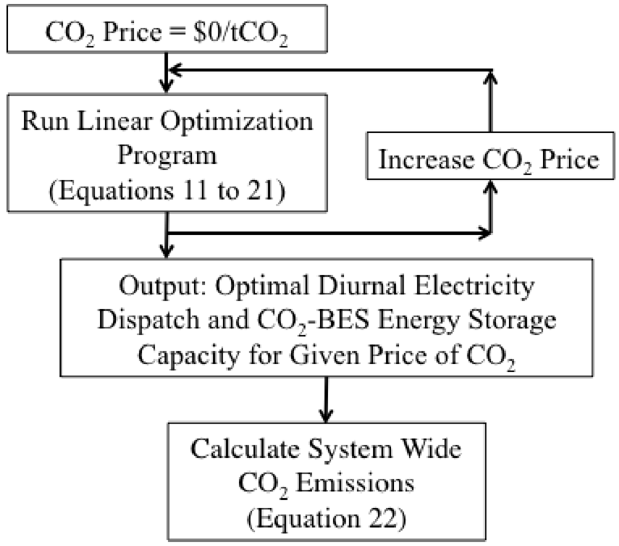

Figure 2. Framework used to determine system wide CO_2 emissions for a given price of CO_2

Since the data from ERCOT was available in 15-minute intervals, we divided the 24-hour day into 96 fifteen-minute intervals. In our model, electricity demand and generation are assumed to be constant within each fifteen-minute interval. The optimization program minimizes system-wide costs because Independent System Operators, like ERCOT, dispatch EGUs based on their variable costs (EIA 2012). EGUs with lower variable costs are dispatched before those with higher operational costs. Our optimization model minimizes costs at each time-step to determine how much electricity should be generated from each component of electricity system throughout the day ($Q_{i,t}$ and $Q_{B,t}$) and the energy storage capacity of the CO_2-BES system, which is the maximum amount of energy stored [MWh] throughout the day ($\max(C_t)$). Energy storage capacities are typically described as the length of time [hours] that electricity can be generated at a given power capacity [MW] and we use the units of MWh to capture both of these variables in one number.

Lastly, we account for the cost of CO_2-BES operation using only the variable cost of discharge, V_B, and the CO_2-BES round trip efficiency, η. Figure 3 and Equations 1 through 10 justify the appropriateness of this simplification.

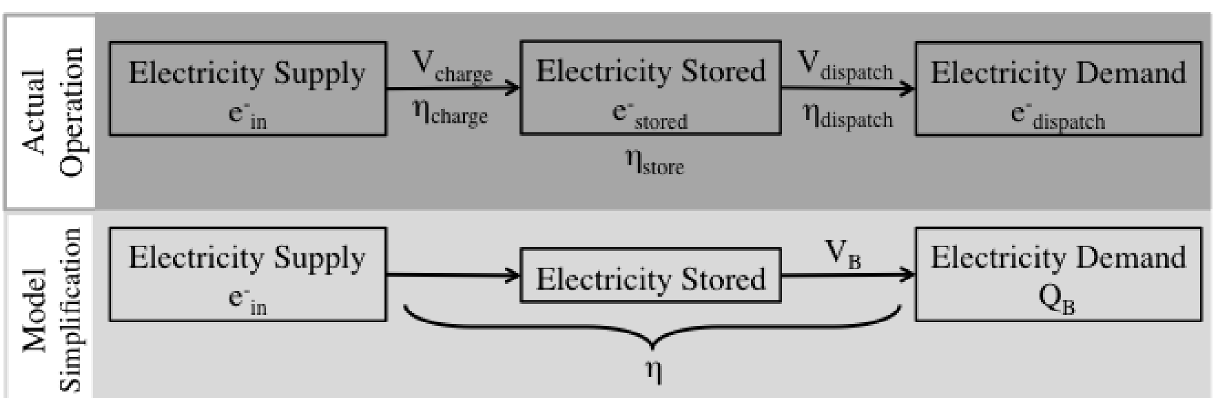

Figure 3. Actual BES operation compared and the simplifications made in the linear optimization program

The amount of electricity dispatched by CO_2-BES, $e^-_{dispatch}$, is the amount of electricity stored multiplied by η_{charge}, η_{store}, and $\eta_{discharge}$:

$$e^-_{dispatch} = e^-_{stored} \cdot \eta_{dispatch} \tag{1}$$

$$e^-_{stored} = e^-_{in} \cdot \eta_{charge} \cdot \eta_{store} \tag{2}$$

$$e^-_{dispatch} = e^-_{in} \cdot \eta_{charge} \cdot \eta_{store} \cdot \eta_{dispatch} \tag{3}$$

As suggested in Figure 3, we define the CO_2-BES round trip efficiency, η, as the product of η_{charge}, η_{store}, and $\eta_{discharge}$ and assign the variable Q_B to $e^-_{dispatch}$ in the model. Therefore, Equation 3 can be re-written as

$$Q_B = e^-_{in} \cdot \eta \tag{4}$$

The total cost, T, of BES operation is the cost of storing and dispatching electricity:

$$T = e^-_{in} \cdot V_{charge} + e^-_{dispatch} \cdot V_{dispatch} \tag{5}$$

In this study, we assume that V_{charge} and $V_{discharge}$ are equal, and assign the variable V_B to this cost. Equation 5 can be further simplified using this information and Equations 3 and 4:

$$T = e^-_{in} \cdot V_{charge} + e^-_{in} \cdot \eta_{charge} \cdot \eta_{store} \cdot \eta_{dispatch} \cdot V_{dispatch} \tag{6}$$

$$T = e^-_{in} \cdot V_{charge} + e^-_{in} \cdot \eta \cdot V_{dispatch} \tag{7}$$

$$T = e^-_{in} \cdot V_B \cdot (1+\eta) \tag{8}$$

Because the total cost decreases with η and our linear optimization program minimizes costs, it is conservative to set BES efficiency as 100% when accounting for costs. If η is assumed to be 100%, the total cost becomes

$$T = 2 \cdot e^-_{in} \cdot V_B \tag{9}$$

By substituting for e^-_{in} using Equation 4, the total cost can be defined in terms of the Q_B and η:

$$T = 2 \cdot \frac{Q_B}{\eta} \cdot V_B \tag{10}$$

Equations 1 through 10 could also be applied to conservatively account for the total amount of CO_2 emissions produced by CO_2-BES operations using only Q_B and η. This estimation of total cost can be seen in the linear program objective function, Equation 11:

Objective function: minimize

$$\sum_{t=0}^{T} \left(\sum_{i} [Q_{i,t}(V_i + \Omega \cdot \varsigma_i)] + 2 \cdot \frac{Q_{B,t}}{\eta}(V_B + \Omega \cdot \varsigma_B) \right) \\ i \in \{1,2,3,4\} \tag{11}$$

Where i=1, 2, 3, and 4 represent nuclear, coal, natural-gas, and wind energy system components, respectively; the subscript B refers to CO_2-BES; V is the variable cost of electricity production [\$/MWh]; Ω is the price of CO_2 [\$/tCO_2]; and ς is the CO_2 emission rate [tCO_2/MWh].

Equation 1 is minimized subject to constraint equations 12 to 21, which are specific to each component of the electricity system:

$$0 \le Q_{k,1} \le \overline{Q_k} \\ k \in \{1,2\} \tag{12}$$

$$Q_{k,t} = Q_{k,t-1} \tag{13}$$

Where $\overline{Q_k}$ is the system wide energy capacities of nuclear and coal system components [MWh]; $Q_{k,1}$ is the amount of electricity dispatched from the nuclear and coal components in the first time period [MWh]; and $Q_{k,t-1}$ [MWh] and $Q_{k,t}$ [MWh] are the amounts of electricity dispatched from the nuclear and coal components in the previous time period and current time period, respectively. Equation 13 shows that the amount of electricity dispatched from nuclear and coal components are constant with time.

$$M \le Q_{3,t} \le \overline{Q_3} \quad (14)$$

$$Q_{3,t} \ge Q_{3,t-1} - R \quad (15)$$

$$Q_{3,t} \le Q_{3,t-1} + R \quad (16)$$

Where $\overline{Q}_3$ is the system wide energy capacity of the natural gas component [MWh]; M is the minimum amount of electricity that must be dispatched by the natural gas energy component at all times; $Q_{3,t-1}$ [MWh] and $Q_{3,t}$ [MWh] are the amounts of electricity dispatched from the natural gas energy component in the previous time period, and current time period, respectively; and R is the maximum (the ramp rate) amount that natural gas dispatch can change in a given time period [MWh].

$$0 \le Q_{4,t} \le W_t \quad (17)$$

Where $Q_{4,t}$ is the amount of electricity dispatched that was generated by wind energy technologies in a given time period [MWh] and W_t is the amount of electricity generated by wind energy technologies that is available for dispatch in a given time period [MWh].

$$C_t = C_{t-1} + \sum_i [Q_{i,t}] - D_t \quad (18)$$

$$C_t \le \overline{Q_B} \quad (19)$$

Where C_t and C_{t-1} are the cumulative amounts of energy stored the current time period and the previous time period, respectively [MWh]; D_t is the electricity demand in the current time period [MWh]; and $\overline{Q}_B$ is the CO_2-BES capacity [MWh]. We set this capacity at a high value (see Table 2) because we do not want the optimal energy storage capacity to be constrained by this value. We assume the CO_2-BES component is initially uncharged (i.e. C_0 is zero).

$$Q_{B,t} \le \eta \cdot C_{t-1} \quad (20)$$

$$D_t \le \sum_i [Q_{i,t}] + Q_{B,t} \quad (21)$$

Equation 20 constrains the amount of electricity that is dispatched from the CO_2-BES component to the cumulative amount of energy stored multiplied by the CO_2-BES efficiency and Equation 21 ensures enough electricity is generated to meet demand. The CO_2 stored in the subsurface gains geothermal energy in between the energy storage and dispatch processes. This increase in energy during the energy storage process, and the reduction in required pumping power due to the thermophysical properties of CO_2, make it possible for a CO_2-BES facility to have a round trip efficiency of 95% (Buscheck 2015).

The system wide CO_2 emissions for a given price on CO_2, S, is determined using Equation 22.

$$S = \sum_{t=0}^{T} \left(\sum_i [Q_{i,t} \cdot \varsigma_i] + Q_{B,t} \cdot \varsigma_B \right) \quad (22)$$

4. DIRECT REDUCTIONS IN CO_2 EMISSIONS FROM CO_2-BES

Throughout the operational lifetime of a CO_2-BES facility, CO_2 is constantly injected in porous and permeable sedimentary basin geothermal reservoirs. The initial few years of this sequestration is called the "charging" period. Once charged, a small portion of the geothermally heated CO_2 can be extracted and used in a CO_2 geothermal power plant to generate electricity when demanded. This extracted CO_2 is held at the surface until electricity supply exceeds demand, at which time the excess electricity can be used to re-inject the CO_2 into the subsurface, additional to the CO_2 injection that is constantly occurring. This sequestration of large volumes CO_2 (i.e., the direct emission reductions) is a major advantage of CO_2-BES compared to PHES and CAES; PHES and CAES can indirectly reduce CO_2 emissions, but neither technology has negative operational CO_2 emissions (Denholm & Kulcinski 2004). For this study, we assume that all CO_2-BES facilities that comprise the CO_2-BES component inject CO_2 at 120 kg/s, which equates to 10,368 tCO_2 of direct CO_2 emission reductions over 24 hours.

5. VALUATION METHODOLOGY

We define the value of CO_2-BES for reducing CO_2 emissions as the monetary benefit of system-wide CO_2 emission reductions divided by the optimal system-wide CO_2-BES energy storage capacity [MWh]. The optimal system-wide CO_2-BES energy storage capacity is defined as the maximum amount of cumulative energy that is stored over the day. The CO_2 price will affect this capacity because it increases the variable cost of generating electricity from facilities that emit CO_2 when generating that electricity.

5.1 Indirect Value to CO_2 Calculation

The difference in the system wide CO_2 emissions between Scenario A and Scenario B is the indirect CO_2 emission reductions that were facilitated by CO_2-BES. The indirect value of CO_2-BES in sedimentary basin geothermal resources to CO_2, I, was determined by multiplying this difference by the CO_2 price and dividing that amount by the optimal energy storage capacity:

$$I = \frac{[S_{ScenarioB} - S_{ScenarioA}] * \Omega}{\max(C_t)} \qquad (23)$$

5.1 Direct Value to CO_2 Calculation

The direct daily CO_2 emission reductions were calculated assuming that all CO_2-BES facilities that comprise the CO_2-BES component of the electricity system use 4km deep sedimentary basin geothermal reservoirs, a CO_2 injection rate of 120 kg/s, and have an injection well to production well pressure difference of 10 MPa. One CO_2-BES facility with these operational parameters could have an energy storage capacity of 1,350 MWh (Buscheck et al. 2016). Following the same methodology as used in Equation 23, the value of directly reducing CO_2 emissions with CO_2-BES, L, was calculated by multiplying the direct CO_2 emission reductions by the value of CO_2 and dividing by the energy storage capacity:

$$L = \frac{10,368 \cdot \Omega}{1,350} \qquad (24)$$

6. RESULTS AND DISCUSSION

Figure 4 shows the difference between total diurnal electricity generation by electricity system component between Scenario A and Scenario B and the optimal system wide energy storage capacity CO_2-BES for every CO_2 price that was modeled. That is, Figure 4 shows the impact that CO_2-BES could have on system wide electricity production over a range of CO_2 prices.

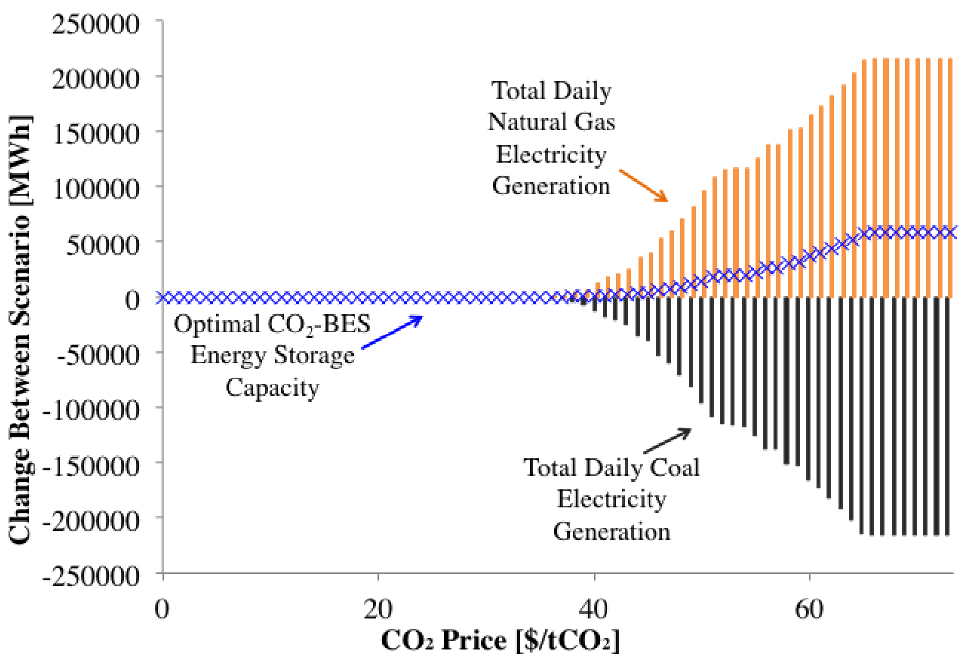

Figure 4. The change in total diurnal electricity generation by electricity system component as a result of CO_2-BES usage and the optimal system-wide energy storage capacity.

Placing a high enough price on CO_2 increases the use of CO_2-BES. The optimal energy storage capacity increases with the price of CO_2 from \$36/tCO_2 to \$66/tCO_2 and this increase in CO_2-BES enables electricity generated by the natural gas component of the electricity system to displace the electricity generated by the coal component. CO_2-BES usage has no impact on either the nuclear or wind energy component dispatch because (1) the flexibility of the electricity grid is high (50% of total energy capacity) in comparison to the amount of electricity generated by wind energy technologies that is available for dispatch and (2) the variable costs of nuclear and wind energy components are lower than coal and natural gas components at all prices of CO_2.

The optimal energy storage capacity plateaus at CO_2 prices higher than \$66/tCO_2 because it is cost minimizing to dispatch as much of the stored electricity as possible. There is a cost associated with initially generating the electricity that is stored and any energy available for dispatch by the CO_2-BES component at time T (24 hours) cannot be used because the day is over. For this reason, the linear optimization program ensures that C_T is as close to zero as possible. The optimal system-wide energy storage capacity would continue to increase if more electricity were stored at prices greater than \$66/tCO_2, but without increasing demand doing so would only increase costs.

Figure 5 shows the value of reducing CO_2 emissions with CO_2-BES and the indirect and direct components of this value.

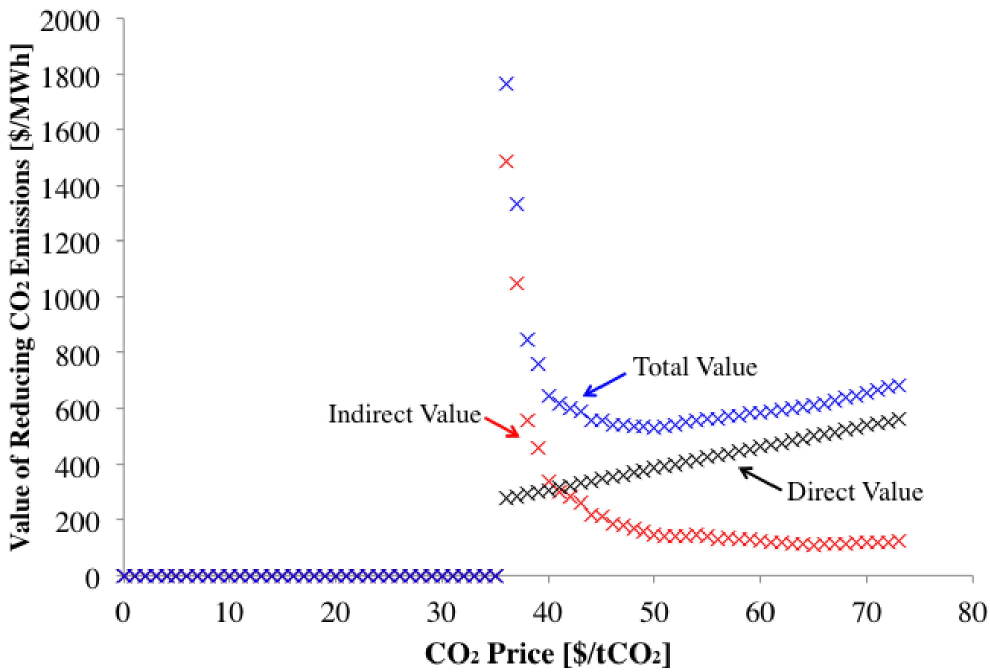

Figure 5. The total value of reducing CO_2 emissions with CO_2-BES and the direct and indirect components of this value as a function of CO_2 price.

The value of reducing CO_2 emissions with CO_2-BES is zero when CO_2 is priced below \$36/tCO_2 because the CO_2-BES component of the electricity system is not dispatched at these CO_2 prices. The direct value increases with the price of CO_2 because this value (Equation 24) is linearly related to the price of CO_2. The indirect value of reducing CO_2 emissions is large as soon as the CO_2-BES component is used because a small system-wide energy storage capacity is optimal. As the price of CO_2 increases, the optimal system-wide energy storage capacity increases more than the indirect CO_2 emission reductions increase, which decreases the indirect value to CO_2 until CO_2 is priced at \$66/tCO_2. As previously discussed, the optimal system-wide energy storage capacity plateaus at \$66/tCO_2 and the indirect CO_2 emission reductions also plateau. Thus, at CO_2 prices higher than \$65/tCO_2, the same number [tCO_2/MWh] is being multiplied by a higher price of CO_2, which makes the indirect value increase. The total value is the sum of the direct and indirect values.

7. CONCLUSIONS

In this study, an approach to determine the value of reducing CO_2 emissions with BES in sedimentary basin geothermal resources was developed and applied to a hypothetical case study using data from the ERCOT electricity system. Our approach determines the value that CO_2-BES could have to reducing CO_2 emissions for various prices on CO_2. We find:

1. The value of BES in sedimentary basins geothermal resources in Texas varies between \$531/MWh and \$1,766/MWh for the prices of CO_2 that the CO_2-BES component of the electricity system is used. These values are far greater than variable cost of CO_2-BES used in this study (\$13.69/MWh).

2. BES can have indirect value to CO_2 even when there is no need to curtail electricity generated by renewable energy technologies. CO_2-BES did not increase the utilization of wind energy technologies in this study because all electricity generated by wind energy technologies available for dispatch was dispatched in all Scenario B simulations. Instead, CO_2-BES enabled electricity generated by natural gas power plants to displace electricity generated by coal-fired power plants, effectively decreasing the need for base load power capacity and increasing the flexibility of the electricity system.

3. The direct value of CO_2-BES to CO_2 is more than double the indirect value for the majority of CO_2 prices associated with CO_2-BES usage. Thus, the value of BES in sedimentary basin geothermal resources to CO_2 is substantially greater than the potential value of PHS or CAES technologies to CO_2. The maximum total value that these conventional BES technologies could have for reducing CO_2 is the indirect value of CO_2-BES to CO_2.

8. ACKNOWLEDGEMENTS

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