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Effects of Bulk Energy Storage in Sedimentary Basin Geothermal Resources on Transmission Constrained Electricity Systems

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ABSTRACT

Sedimentary basin geothermal resources and carbon dioxide (CO_2) can be used for bulk energy storage (CO_2-BES), which could reduce the capacity, and thus cost, of high voltage direct current (HVDC) transmission infrastructure needed to connect high quality wind resources to distant load centers. In this study, we simulated CO_2-BES operation in the Minnelusa Aquifer in eastern Wyoming and used those results in an optimization model to determine the impact that CO_2-BES could have on the revenue of a wind farm that sells electricity to the California Independent System Operator (CAISO) market under varying HVDC transmission capacity scenarios. We found that the CO_2-BES facility can dispatch more electricity than was previously stored because of the geothermal energy input. While CO_2-BES performance degrades because of geothermal resource depletion, our results suggest that a CO_2-BES facility could increase revenue from electricity sales throughout its lifetime by (1) increasing the utilization of HVDC transmission capacity, and (2) enabling arbitrage of the electricity prices in the CAISO market. In some cases, adding CO_2-BES can provide more revenue with less HVDC transmission capacity.

1. INTRODUCTION

Using carbon dioxide (CO_2) as a heat extraction fluid may enable the use of sedimentary basin geothermal resources for electricity production because CO_2 has increased heat advection capabilities and mobility compared to brine (Adams et al. 2014; Adams et al. 2015; Randolph & Saar 2011; Garapati et al. 2015). Sedimentary basin geothermal resources and CO_2 could also be used for bulk energy storage (CO_2-BES) which would permanently isolate large volumes of CO_2 from the atmosphere while time-shifting the electricity that is generated by other energy technologies within the electricity system (Buscheck, Bielicki, Edmunds, et al. 2016). CO_2-BES could thus address some of the challenges of supplying large portions of electricity demand with variable renewable energy technologies (e.g., solar photovoltaics and wind turbines). One such challenge is that high quality variable renewable energy resources may not be located in the same region that the electricity is demanded. For example, much of the high quality wind resource in the United States is located in areas with low population densities (e.g., central part of the country), and thus low electricity demand (U.S. DOE 2008). Whereas high population densities are located on the coasts where there are less quality wind resources. High voltage direct current (HVDC) transmission lines can be used to transmit electricity long distances in order to provide the electricity that is demanded at major load centers, but HVDC transmission infrastructure is expensive and the fluctuations in the amount of electricity that is generated from variable wind and solar energy technologies makes it difficult to size the capacity of the HVDC lines. Low capacity HVDC transmission lines are cheaper than high capacity lines, but they may not have the capacity to accommodate all of the peaks in variable electricity generation. As such, electricity that is generated in excess of the HVDC transmission line capacity would be wasted and would decrease the revenue that could be earned from selling electricity. CO_2-BES could store the excess electricity and then transmit that stored electricity later when electricity generation is below line capacity. As such, implementing CO_2-BES where the variable electricity is generated could facilitate the installation of cheaper, lower capacity HVDC lines, without sacrificing the amount of electricity that could be transmitted, and revenue that would be earned, from the variable wind or solar energy technologies. In this paper, we estimated the additional transmission capacity utilization and revenue that could be realized from selling electricity in the California Independent System Operator (CAISO) market by adding a CO_2-BES facility to a wind farm in eastern Wyoming. We chose Wyoming as a case study because it has a relatively small population, substantial high-quality wind resources (Class 3 to 7), and sedimentary basin geothermal resources that are favorable for CO_2-BES.

2. METHODS

Our framework in Figure 1 includes a process-level simulation of the performance of CO_2-BES and a mixed-integer linear optimization model that is adapted from an existing approach in order to incorporate CO_2-BES (Denholm & Sioshansi 2009). The optimization model maximizes the revenue made by a wind farm with CO_2-BES from selling electricity to a distant load center over a year, given the CO_2-BES process-level parameters, the HVDC transmission capacity, and assuming perfect foresight of wind availability and wholesale electricity prices. We investigated HVDC transmission capacity scenarios from 100 MW to 1,000 MW in increments of 100 MW. We calculated the revenue that the wind farm would receive by multiplying the amount of electricity that would be transmitted by the wholesale electricity price. We assumed that curtailment only occurred if selling electricity would yield negative revenue (i.e., the price of electricity is negative), or if the amount of electricity that is generated exceeds the capacity of the HVDC transmission line.

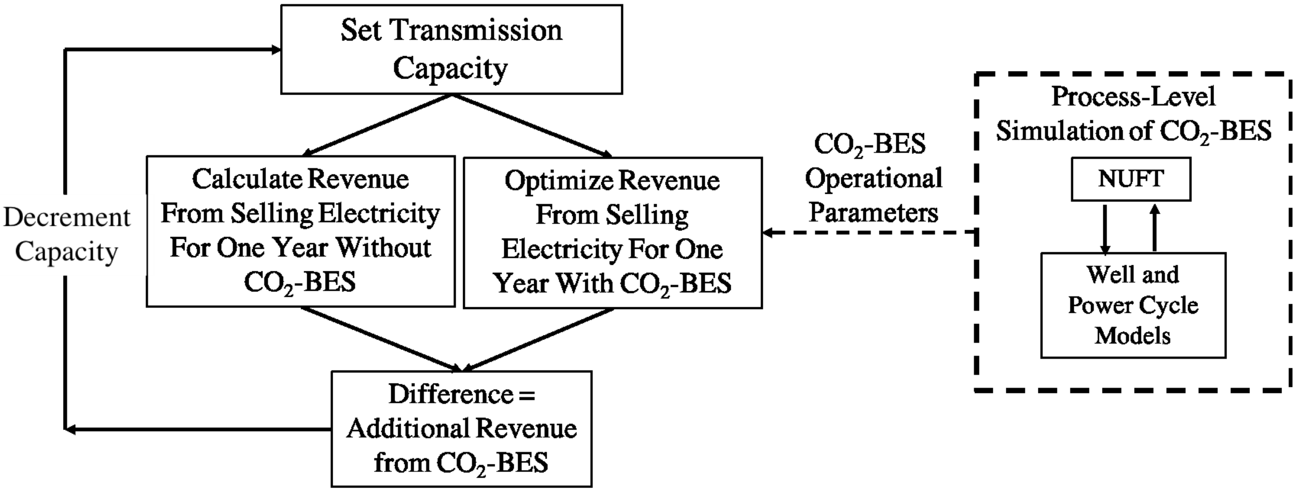

Figure 1: The General Framework. The CO_2-BES process level simulation is shown with a dashed line because it is not directly coupled with the optimization model, but rather informs inputs in some constraint equations.

We used the Non-isothermal Unsaturated Flow and Transport (NUFT) code (Hao et al. 2012) to simulate the reservoir and estimate the performance of a CO_2-BES facility. The important characteristics of this performance include the power storage capacity and the round-trip efficiency. We parameterized the model with data on a case study of the Minnelusa Aquifer in the Powder River Basin (e.g., depth, thickness, permeability) in eastern Wyoming (USGS 2013a). For the operation of the CO_2-BES facility, there is 3 to 5 year "charging" period where CO_2 is compressed and injected into a porous and permeable aquifer that is at least 800 m deep in order to store energy as pressure. In-situ brine is produced to the surface and then re-injected to control the migration of the CO_2 plume and manage the overpressure in the subsurface. During operation, the CO_2-BES facility can dispatch electricity when it is demanded by producing geothermally-heated CO_2 and brine to the surface. The heat in these fluids is used to generate electricity in a direct CO_2 power cycle and indirect brine power cycle. The produced CO_2 is re-injected into the subsurface and the produced brine is placed in holding ponds at the surface and reinjected as necessary to control the reservoir overpressure and, along with CO_2 that has been captured from a point source, to store excess energy.

We coupled the reservoir results with a well model and two power cycle models, which were adapted from prior work (Adams et al. 2015). The well model simulates fluid flow through a well using the first law of thermodynamics, patched Bernoulli, and the conservation of mass equations. The power cycle models simulate electricity generation and consumption from a direct CO_2 power cycle and an indirect brine power cycle. The total power storage and output capacities of the CO_2-BES facility is the sum of power generated and consumed by both cycles.

The performance of the CO_2-BES facility can decrease over the 30-year simulated lifetime because it could extract geothermal heat faster than the resource is recharged by the geothermal heat flux. The rate at which the heat resource is depleted depends in part on how the CO_2-BES facility cycles between dispatching electricity (discharging) and consuming or storing (charging) it. For this study, we assumed that the facility continuously cycled between charging for 12 hours and discharging for 12 hours in the process level simulation. Given the potential degradation in performance of the CO_2-BES facility, we implemented in the optimization three different cases regarding the performance of the facility. In one case, we assumed that the power storage capacity and round-trip efficiency in the optimization model was equal to the values from the first year of the process-level simulation. In the second case, we used the average power storage capacity and round-trip efficiency over the 30 years of process-level simulation. In the last case, we used the power storage capacity and round-trip efficiency from the last (i.e., 30th) year of process-level simulation. We calculated the difference in estimated revenue between operating with and with CO_2-BES for each case separately.

2.1 Data

2.1.1 Revenue Maximizing Optimization Model Inputs

For the wholesale price of electricity in the CAISO market, we used the 2016 day-ahead market electricity price data from a node in Oakland, California (node STATIN-L_7_N001) (CAISO 2017). We used the Western Wind Data Set from the National Renewable Energy Laboratory (NREL 2010) to estimate the hourly power production of a wind farm in eastern Wyoming. We selected an area in which the estimated output in the NREL data set was 1.06 GWe capacity. Our case study in Wyoming and California are about 990 miles apart and we assumed the transmission losses over this distance were 6% (Denholm & Sioshansi 2009). We also assumed that CO_2-BES operating costs are \$15/MWh, which is within the range of typical operating costs for geothermal power plants that has been reported by the U.S. Department of Energy (DOE) and above other estimates that are available provided elsewhere (Kaplan 2008; EIA 2017; DOE 2018).

2.1.2 Sedimentary Basin Geothermal Resource Data

The most likely subsurface parameters of the Minnelusa Aquifer are a permeability of 10^{-13} m^2, porosity of 16%, thickness of 120 m, and a depth of 2.74 km (USGS 2013a). As a result, we assumed the CO_2-BES facility was operating within a homogeneous sedimentary basin geothermal resource with those characteristics. We assumed the geothermal temperature gradient was 42 °C/km, which we based off a combination of North American sedimentary basin, geothermal heat flux, and CO_2 storage datasets (NETL 2015; Frezon et al. 1983; Fuis et al. 2001; Jachens et al. 1996; Langenheim & Jachens 1996; Mooney & Kaban 2010; USGS 2013b; Jachens et al. 1995).

3. RESULTS

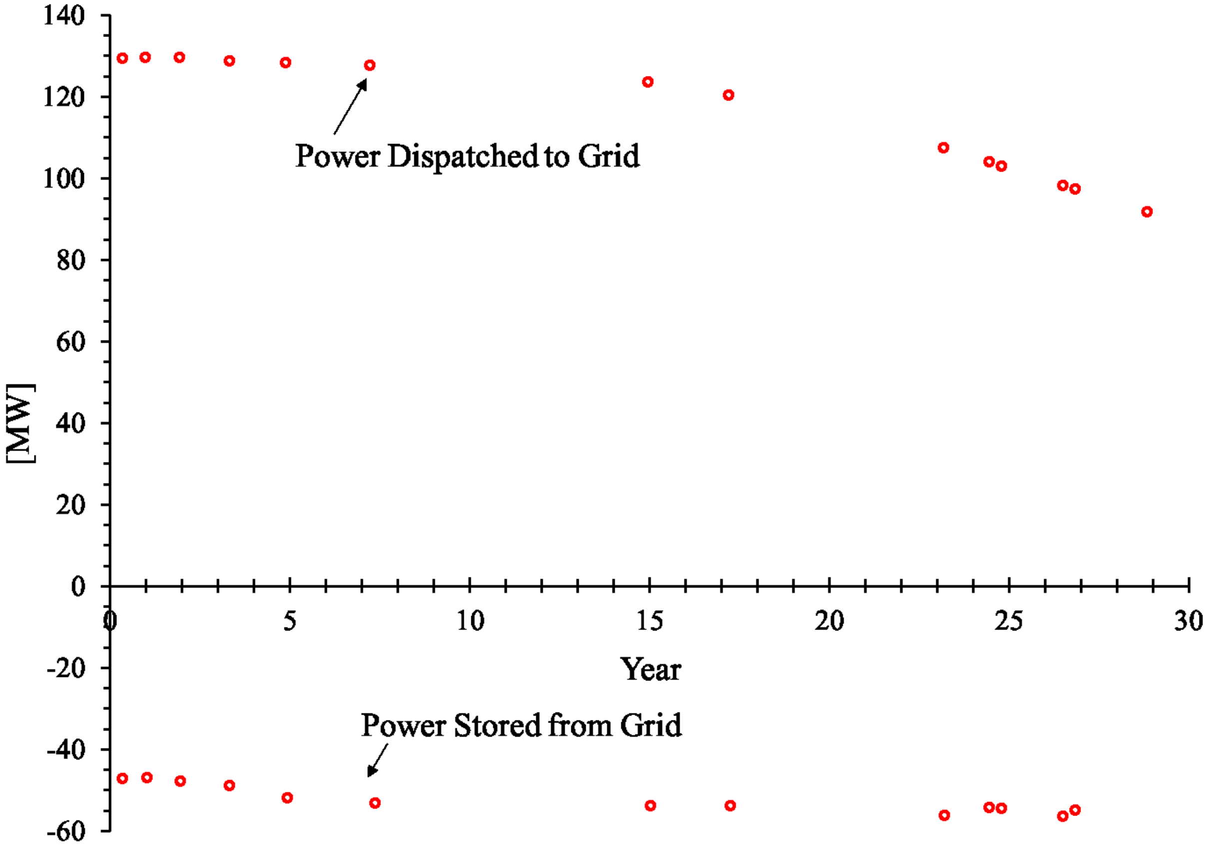

Figure 2: Performance of a Simulated CO_2-BES Facility Using a 12-hour Charge, 12-hour Discharge Cycle in the Minnelusa Aquifer, within eastern Wyoming. The data points are irregularly spaced because the time required to simulate power cycle operation for all data generated by NUFT is computationally prohibitive.

In the first year of operation, our results suggest that the CO_2-BES facility in the Minnelusa Aquifer consumes ~47 MW when it is storing energy from the grid, and discharges ~130 MW to the grid, for a round-trip efficiency of 2.75 (130/47) (Figure 2). More electricity can be dispatched than was stored because of the addition of energy from the geothermal heat flux. But this power output decreases over time to ~90 MW, and the round-trip efficiency decreases to 1.66, at the end of the end of the simulated 30-years of operation. There are two reasons for the reduction in the round-trip efficiency over time. First, the power output capacity decreases over time because the geothermal heat is extracted faster than it can be replenished. Second, consumption of energy for storage increases to ~55 MW by year 7, because reservoir overpressure increases and thus more energy is needed to compress and inject CO_2 and brine. This overpressure increases in part because of our assumption that CO_2 is constantly injected over the full 30 years. The overpressure does not continue to increase after 7 years because we do not reinject (i.e., we permanently remove) a portion of the produced brine after that time to limit overpressure to 10 MPa. Alternative CO_2 injection strategies could be employed to moderate the increase in overpressure (Buscheck, Bielicki, White, et al. 2016; Hunter et al. 2017), but with our operation ~114 $MtCO_2$ are injected, and permanently isolated from the atmosphere, over the 30 years.

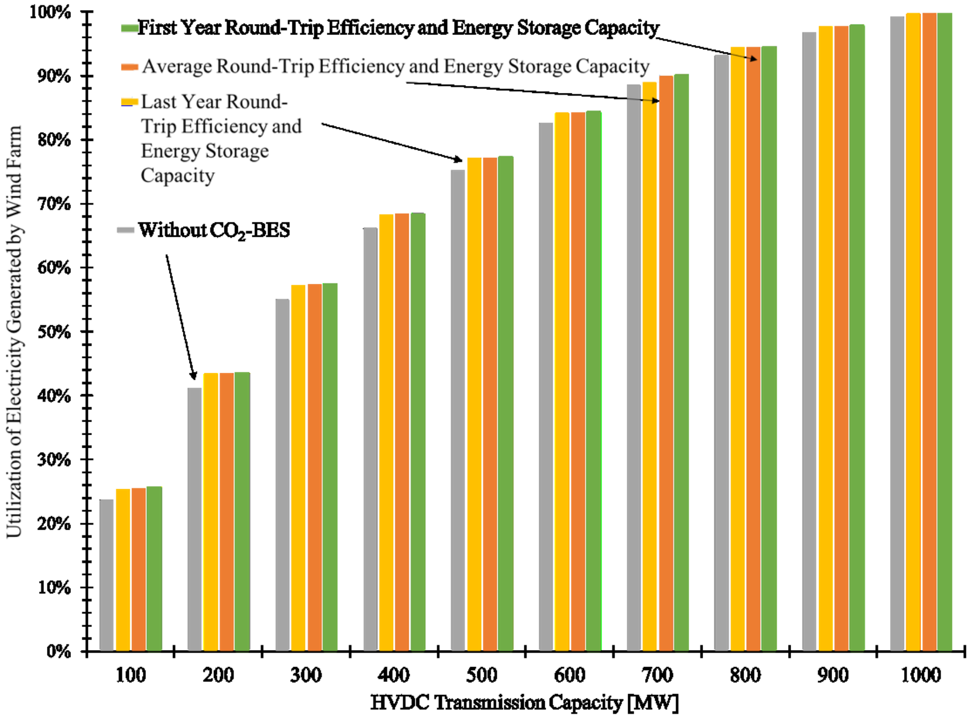

Figure 3: Percent of Electricity Generated by the Wind Farm that Was Not Curtailed Due to Insufficient Transmission Capacity

For every HVDC transmission line capacity that we investigated, CO_2-BES enables an increased utilization of the electricity generated by the wind farm (Figure 3). Further, for a given HVDC transmission capacity, the utilization of electricity generated by the wind farm is relatively insensitive to the CO_2-BES round-trip efficiency and energy storage capacity (i.e., to the decrease in performance over time as in Figure 2). As a consequence, it is unlikely that depleting the geothermal resource will have a substantial impact on the amount of electricity that is generated by the wind farm that would be curtailed over the lifetime of a CO_2-BES facility.

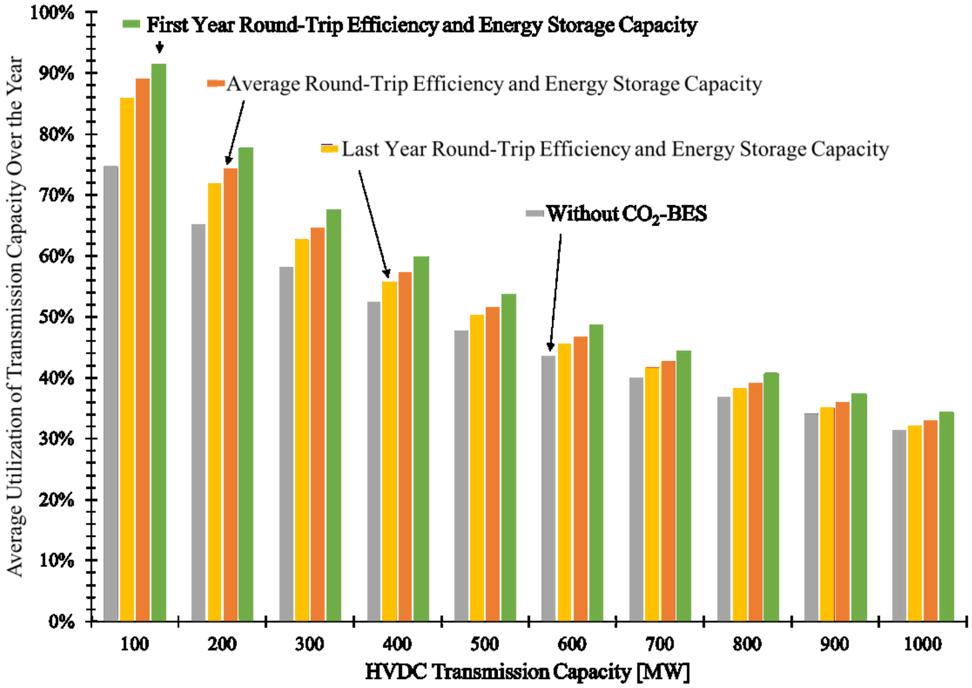

Figure 4: Percent of Possible Energy that Could Have Been Transmitted from Wyoming to California Over the Year.

The addition of CO_2-BES results in an increased utilization of the available transmission capacity in all HVDC transmission capacity scenarios that we investigated (i.e., in Figure 4, the colored bars are taller than the grey bars). Unlike the utilization of electricity generated by the wind farm (Figure 3), the transmission capacity utilization is sensitive to the CO_2-BES round-trip efficiency and energy storage capacity: for all HVDC transmission capacity scenarios, CO_2-BES increased the utilization of transmission capacity the most when first year parameters were used. As such, the depletion of the geothermal resource primarily impacts the ability of CO_2-BES to arbitrage electricity prices when it is not operating as a transmission asset. As a consequence, the additional revenue earned from adding a CO_2-BES facility to the wind farm is largest when the first-year round-trip efficiency and energy storage capacity were used (Figure 5).

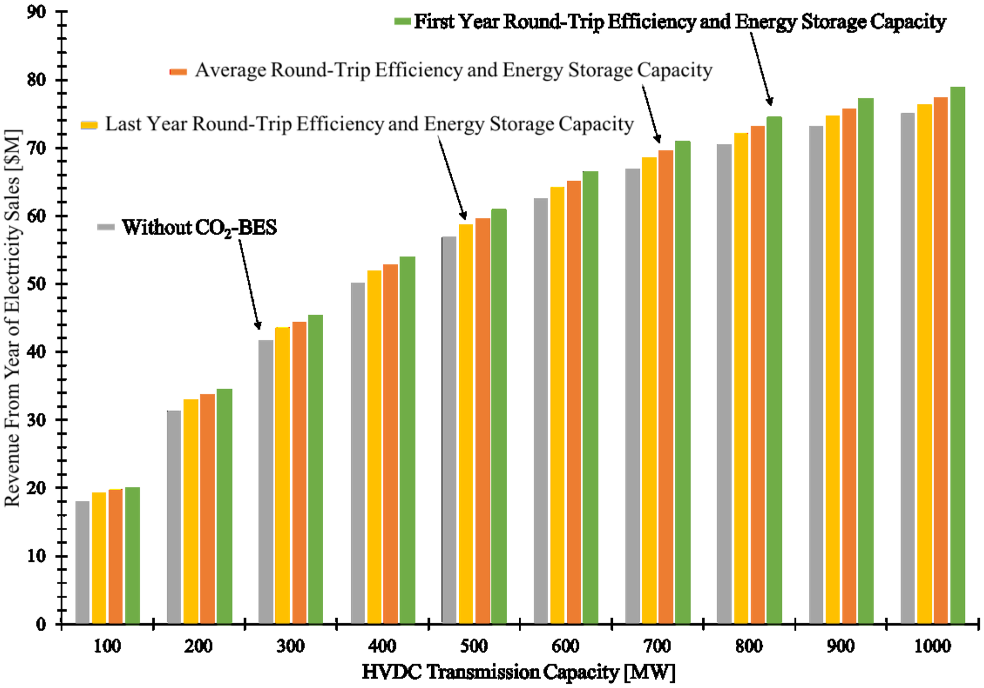

Figure 5: Revenue from Selling Electricity to the CAISO Electricity Market with and without CO_2-BES

For every HVDC transmission line capacity that we investigated, wind farms with CO_2-BES facilities earn more revenue than those without CO_2-BES (i.e., the colored bars are taller than the grey bars in Figure 5). This increase in revenue occurs because CO_2-BES allows the wind farm operator to (1) sell electricity when the electricity price is high and buy and store electricity when the price is low, and (2) increase the utilization of existing transmission capacity. As a result, a wind farm operator could add a CO_2-BES facility and earn more revenue with less HVDC transmission capacity. For example, the revenue with a 900 MW HVDC transmission capacity is about $2M more with CO_2-BES implemented than would be earned with a 1,000 MW HVDC line without CO_2-BES (Table 1). With transmission capacity scenarios below 700 MW, however, CO_2-BES does not enable wind farm operators to earn more revenue with less HDVC capacity because there are fewer instances throughout the year in which the wind farm is generating less electricity than the HVDC transmission capacity. As a result, there are fewer opportunities to increase revenue by selling electricity that was previously stored.

Table 1: Difference in Revenue for Wind Farms with CO_2-Bulk Energy Storage Relative to Wind Farms Without CO_2-Bulk Energy Storage [$M]. Bold items indicate where a lower HVDC transmission line capacity has more revenue with CO_2-BES than for the higher transmission line capacity without CO_2-BES.

<table>
<tr><th></th><th></th><th colspan="4">With CO2-Bulk Energy Storage
First-Year | Average | Last-Year</th></tr>
<tr><th></th><th>HVDC Line Capacity (MW)</th><th>700</th><th>800</th><th>900</th><th>1000</th></tr>
<tr><td rowspan="4">Without CO2-Bulk Energy Storage</td><td>700</td><td>3.99 | 2.68 | 1.66</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>800</td><td>**0.43** | -0.87 | -1.90</td><td>3.99 | 2.64 | 1.59</td><td>X</td><td>X</td></tr>
<tr><td>900</td><td>-2.27 | -3.58 | -4.61</td><td>**1.28** | -0.06 | -1.12</td><td>3.95 | 2.57 | 1.50</td><td>X</td></tr>
<tr><td>1000</td><td>-4.10 | -5.40 | -6.43</td><td>-0.54 | -1.88 | -2.93</td><td>**2.13** | **0.75** | -0.32</td><td>3.84 | 2.42 | 1.32</td></tr>
</table>

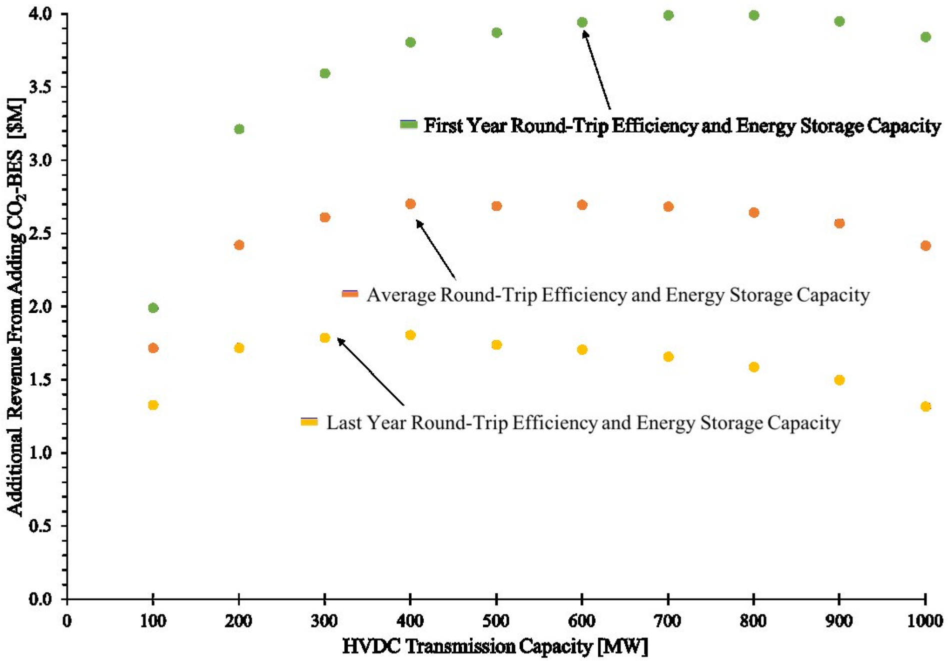

Figure 6: Additional Revenue Earned from Adding a CO_2-BES Facility to the Wind Farm in eastern Wyoming

While the additional revenue earned from a CO_2-BES facility is likely to decrease each year of (continuous) operation, all CO_2-BES round-trip efficiency and energy storage capacity scenarios that we investigated resulted in increased revenue compared to the wind farm without CO_2-BES (Figure 6). Further, there the additional revenue peaks for a specific HVDC transmission line capacity, and this optimal size decreases as the CO_2-BES facility is continuously operated. This peaking profile occurs because there is less opportunity to increase revenue through increasing the utilization of the transmission capacity as the transmission capacity increases. Instead, the additional revenue earned from CO_2-BES in higher HVDC capacity scenarios is primarily a result of arbitrage, compared to the combination of arbitrage and increasing the utilization of the transmission capacity. The HVDC transmission capacity at which peak additional revenue occurs depends on the CO_2-BES round-trip efficiency and energy storage capacity scenario because the ability of CO_2-BES to arbitrage electricity prices is sensitive to the geothermal heat depletion.

4. CONCLUSIONS

Or prior work has shown that CO_2 can be used in sedimentary basing geothermal resources to produce electricity (Adams et al. 2014; Adams et al. 2015; Randolph & Saar 2011; Garapati et al. 2015) (CPG system) and to store and dispatch electricity (Buscheck, Bielicki, Edmunds, et al. 2016) (CO_2-BES system). Here, we investigated the potential to use a CO_2-BES facility in conjunction with a wind farm to earn revenue and reduce the size of an HVDC transmission line. We simulated the performance of a CO_2-BES facility in eastern Wyoming assuming a 12-hour charge, 12-hour discharge cycle repeated over 30 years and then used the results in a revenue-maximizing optimization model where the electricity was to be transmitted by HVDC line to Oakland California. We found that:

1. More electricity can be dispatched by a CO_2-BES facility than was previously stored because of the energy input from the geothermal heat flux. Over the 30-year operational lifetime of the CO_2-BES facility, the power output capacity and round-trip efficiency decrease because the geothermal heat is extracted at a faster rate than the geothermal heat flux can replenish the geothermal resource.

2. Adding a CO_2-BES facility to a wind farm can enable additional revenue because CO_2-BES allows wind farm operators to arbitrage electricity prices while increasing the utilization of existing HVDC transmission capacity. In some cases, adding CO_2-BES can provide more revenue with less HVDC transmission capacity.

3. Adding a CO_2-BES facility to a wind farm will likely increase revenue the most during the first year of operation because depleting the geothermal resource reduces the ability of a CO_2-BES facility to arbitrage electricity prices when it is not operating as a transmission asset. Despite the decrease in revenue resulting from geothermal resource depletion, it is unlikely that a CO_2-BES facility would cease to provide additional yearly revenue to a wind farm operator over its 30-year lifetime.

It is likely that our results provide a floor for the revenue that could be earned by coupling CO_2-BES with a wind farm. For example, in an actual operation, it is likely that there will be idle periods where neither charging nor discharging occurs, or times when it may be desirable to charge or discharge for unequal lengths of time. Further, the optimization model used in this study was myopic in the sense that it optimized the use of the CO_2-BES facility over a single year and did not consider the impact that the charging and discharging profile may have on operation in subsequent years. If any of these assumptions were removed, the performance of the CO_2-BES facility may not degrade as quickly because there would be less heat depletion and less build-up of reservoir overpressure over time. In addition, with a positive CO_2 price, a CO_2-BES facility could earn additional revenue from the permanent geologic CO_2 storage. This additional source of revenue was outside the scope of this study, but it would enhance the profitability of adding CO_2-BES, and help to offset the decrease in revenue that results from the degradation of its performance over time.

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