Assessment of Economic Impacts of Cryogenic Carbon Capture in a Power Grid Environment

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Project Summary

As climate change influences policy more and more, there will be an increasing need for low-carbon and carbon-free sources of power. Many of these sources are intermittent and create problems in power grids when they come on at inopportune times. Researchers have been introducing ways to deal with this, and the most likely solution seems to be large scale energy storage. This project seeks to propose a solution to both carbon emissions and energy storage. A power grid is modeled in the General Algebraic Modeling System (GAMS). Cryogenic Carbon Capture (CCC) is implemented in this grid environment so that the operating cost, penalties, and carbon emissions can be evaluated against a grid without CCC. This type of analysis has never been done by using a CCC plant with energy storage.

Main contributions

- Created a dispatch model that represents the Electricity Reliability Council of Texas (ERCOT)
- Added Cryogenic Carbon Capture with energy storage to the power grid
- Compared operating costs of the optimized grid with and without CCC
- Compared CO_2 emissions for optimized grid with and without CO_2

Abstract

As concerns over climate change grow, the demand for carbon free power generation continues to increase. Many attempts to find solutions have been considered, but with each approach more issues arise. First, the addition of intermittent power sources, such as wind, to the power grid causes uncertainties in the production of electricity. Second, the need for reduction of carbon in current fossil burn sources has led to the creation of carbon capture systems that come with high energy and monetary costs. Many dissertations exist to solve each of those problems individually. Energy storage modelling and optimization on the grid have been attempted in many different forms, some proving to be profitable ventures. Carbon capture systems have also been optimized to significantly reduce the parasitic load induced by implementing one of these systems. This paper explains the modeling and optimization of the two in tandem to get the best results. A Cryogenic Carbon Capture (CCC) system with energy storage is modeled in on a grid scale to investigate the potential for cost and CO_2 emission savings.

Introduction

In attempt to eliminate the harmful effects of fossil fuels on the environment, many options have been considered that look for carbon free power sources or look to mitigate the amount of carbon emitted through fossil fuel processes. Wind, Solar, and other intermittent renewables create issues because the current power grid configuration cannot handle an imbalance in electricity production and demand. Many people are proposing some sort of grid scale storage as a solution. Large battery systems have been implemented that can accommodate the imbalance resulting in large savings. Other examples of large scale energy storage systems include pumped hydro, compressed gas, and molten salts. All of these have their advantages and disadvantages.

Heavy scrutiny is placed on carbon dioxide producing plants. Public opposition, legislation such as the clean power plan, and environmental groups are all placing pressure on power producers to emit less carbon. One idea, as opposed to shutting down fossil burning plants, is to use some type of carbon capture system (CCS) to capture and store the CO_2 rather than emitting it. Even though CCS can effectively remove upwards of 90% of CO_2, it comes with a very high energy cost, sometimes up to 40% times that of the plant. However, the optimization of these systems in a grid-scale model can reduce the parasitic energy usage from CCS. Optimization of these processes can lead to a parasitic load as little as 14%.

Literature Review

Using a PROMOD (Ventyx Promod IV) software model, a battery energy storage system was applied to a power system from Brues to West Bellaire. When the energy storage system was incorporated into the model, the congestion cost was cut over $9 million for the modeled year of 2012 as recorded by Abdurrahman and Baker [1]. Another technique developed by Ramirez-Elizondo [7] for incorporates energy storage systems into a unit commitment model with multiple energy systems. The technique showed the general conclusion that an energy storage system incorporated into a multiple energy system unit commitment model influenced scheduling and dispatch.

Yunfeng and Chuangxin [9] looked into a form of power storage incorporated into a unit commitment model. This reduced the cost of power generation of emergency demand loads by performing arbitrage and by reducing the spinning reserve demand through corrective actions. Harkin and Hoadley [4] explored the trade-off between costs and net power. Their work dealt with a fossil-fuel power plant equipped with a carbon capture system was optimized using multi-objective optimization and automated heat integration. Through optimization the energy penalty of the carbon capture system was reduced from 38% without optimization to 14% with optimization. Economic considerations suggest a more modest decrease from 38% without optimization to 25-30% with optimization. Lou and Wu's [5] work deals with spinning reserves. In their work, a 26-unit power grid with a carbon capture system was optimized to observe the impact of the carbon capture system's relationship with the spinning reserve. In times of emergency demand, the carbon capture system parasitic load can be reduced, allowing a lesser capacity spinning reserve to be maintained; thereby providing greater flexibility in optimizing the system with regards to the spinning reserve. The authors created an optimization model to coordinate the carbon capture system and the spinning reserve with overall power generation. The 26-unit model with carbon capture showed that carbon capture systems have a significant impact on overall cost and on the spinning reserve requirements.

Safdarnejad and Kennington [2] explored the impact of CCC on power plant performance. A Cryogenic Carbon Capture system was applied to a fossil-fuel power plant in a multiple energy system power grid. The CCC system showed quick response to changes in electricity demand as well as energy storage capacity, thereby allowing greater use of renewable energy resources in the power grid. This in turn decreased the carbon emissions of the plant and operating profit was valued at $13K/hr and $21K/hr for summer and winter cases, respectively. Further, Cohen [8] at the University of Texas researched the economic benefits of a carbon capture system on a power grid. Instead of operating the carbon capture system at full load, the carbon capture system was dynamically operated. The dynamically operated carbon capture system showed potential to save the power grid $10-100 million per year. In essence, the carbon capture system was operated at more economically beneficial time periods through dynamic modeling which led to the significant profit gains.

Lu, Lou, and Wu [9] developed an economic power dispatch model in a low-carbon economy, incorporating both the fuel cost and the carbon emission cost in the objective function. Tested on a 3-unit system, the model showed that the carbon capture system benefitted the 3-unit system in environmental and economic ways. It concluded that coal price and carbon trading price have a highly impactful effect on the cost of the entire system. Finally, Kang and Brandt [3] researched optimization of a hybrid fossil-fuel, natural gas, and wind energy system with a temperature swing absorption carbon capture system. Via optimization of the system, a 20% operating profit was shown in comparison to heuristic means. The parasitic load of the carbon capture system was greatly mitigated and the fluctuating wind generation was used more efficiently through the optimization of the system.

It has been shown that many different types of energy storage have been tried and some with relative success to be able to effectively utilize intermittent energy sources. It has also been proven that this has great potential for energy and monetary savings. Many studies have also been done to validate the use of a carbon capture system to continue to operate fossil fuel plants to produce electricity without so many carbon emissions. Many articles have shown that optimizing these processes can reduce the parasitic load to make the option look more attractive. One thing that had never been tried was to try to combine the two. There is a significant opportunity to try to utilize the Cryogenic Carbon Capture system as an energy storage system on the grid. This would be two fold in filling the need to maintain power production while reducing carbon emissions. Green energy could be utilized and fossil fuel systems would be used in harmony with these systems while capturing most of the effluent carbon. This paper seeks to model and optimize the use of the two. This is done using the GAMS program.

Theory

Power Grid Modeling is a very useful method for maximizing carbon free energy. Since the introduction of more intermittent energy sources, difficulties have existed to maintain a balance between energy production and demand. When demand is in excess, power will be shut off unless generators are used to make electricity which can be very costly. Conversely, when the electricity supply is higher than the demand, the excess must be wasted and go directly to ground unless some form of storage exists. As the intermittent sources rise into global energy portfolios, energy storage systems and thus power grid modeling have become equally important. If managed and optimized well, power grids can effectively utilize all intermittent energy with relatively few storage inefficiencies.

Cryogenic Carbon Capture (CCC) is a process by which carbon dioxide (CO_2) is removed from a gas stream by means of extreme cooling. The CO_2 liquefies at nearly -110 °F and can be separated from the other streams. The process to cool the refrigerant, which in turn condenses the CO_2, is highly energy intensive, which is one of the setbacks of the CCC process. However, this refrigerant can be stored quite easily. It is therefore possible to make excess cooling liquid when intermittent renewable power sources such as wind and solar are generating power and use it when it is most convenient for the optimization. This load is much easier load to adjust than adjusting the production of a major plant. Essentially, the CCC system is able to make use of all power when intermittent sources come online, when other systems would not have been able to accommodate this and electricity would have been forced to ground. It is also performing the very valuable task of capturing carbon in the process.

Model Inputs

Each plant has its own individual parameters, so it is necessary to import a pant database. Many of these parameters were obtained from [8]. Table 1 lists all the variables that are imported. A p subscript denotes the variable is dependent on the plant. A t subscript denotes dependence on time.

Table 1 Variables imported from plant database

Symbol	Parameter
$\boldsymbol{p}$	Plant name
$\boldsymbol{OM_p}$	Variable operating and maintenance cost ($/MWh)
$\boldsymbol{H_p}$	Heat rate (MMBTU/MWh)
$\boldsymbol{R_p}$	CO_2 emission rate (tCO_2/MWh)
$\boldsymbol{x_p^{min}}$	Minimum output (MW)
$\boldsymbol{x_p^{max}}$	Maximum output (MW)
$\boldsymbol{\delta_p}$	Ramp rate (MW/min)
$\boldsymbol{L_t}$	Electricity Demand (MW)
$\boldsymbol{W_t}$	Wind energy (MW)

Costs are found by using the heat rate, VOM cost, and CO_2 emission rates. Power generation must stay within the respective plant's specified minimum and maximum limit. The ramp rate limits the change in power production that each plant can have per hour, either up or down. Wind energy is imported and subtracted directly from the electricity demand to form net load. The optimizer then tries to match the power production to this net load value. That ensures that all the wind energy is used, which is a realistic scenario with the way government regulations and utility policies are currently set up.

Model Formulation

This model is set up as a non-linear program (NLP) that utilizes the Interior Point Optimization (IPOPT) solver package. The model is implemented in GAMS, which is an algebraic modeling language for large-scale linear, non-linear, or mixed integer optimization problems [1]. The language was chosen for this project because it is capable of handling multiple sets. For example, many variables for this project vary with both individual plant and time. Because GAMS could handle multiple sets, code can be written more efficiently.

The CCC model was set up in [2]**.** The formulation outlined in that paper was taken, converted to GAMS, and used in conjunction with grid level optimization. The only modifications that needed to be made dealt with the connection of load data to the CCC parameters. Instead of all of the demand being fed to the CCC system, only the demand that the CCC plant needed to cover was used.

The grid level optimization starts with the input of load, or power demand. The solver then varies the amount of power generation from each specific unit to match demand. Generation units include nuclear, coal, coal with carbon capture, natural gas combined cycle (NGCC), open cycle gas turbine (OCGT), hydro, and wind power. The optimal solution minimizes both cost and demand vs generation imbalances. The general form of the objective function is set up in Equation 1.

$$\min \varphi = C_{fuel} + C_{vom} + C_{co2} + C_{ccs} + P_{under} + P_{over} \tag{1}$$

Table 2 Variable Declarations for Equation 1

Variable	Meaning
$\boldsymbol{C_{fuel}}$	Cost of power production from fuel
$\boldsymbol{C_{vom}}$	Cost of power production from operation and maintenance
$\boldsymbol{C_{co2}}$	Cost of co_2 from penalty
$\boldsymbol{C_{ccs}}$	Cost of power production from carbon capture system and storage (if applicable)
$\boldsymbol{P_{under}}$	Cost penalty for under generation
$\boldsymbol{P_{over}}$	Cost penalty for over generation

One important soft constraint is the penalties for over and under production. The penalty equations are outlined in Equation 2. slk_{pos} and slk_{neg} are slack variables that represent the positive and negative power production at each time step. $x_{p,t}$ represents power generation for each plant and time step. Equation 2.2 and 2.3 calculate the total cost penalty over the time horizon. The slk_{neg} is multiplied by a penalty in units of $/MWh. The same is true of equation 2.3 for positive slack. Because the objective function seeks to minimize cost, both slack variables will be minimized. In conjunction with real grid scenarios, the penalty for under generation is much steeper then over generation.

$$\sum_{p} x_{p,t} + slk_{pos} - slk_{neg} = L_t \tag{2.1}$$

$$P_{under} = \sum_{t} slk_{neg} * I_{under} \tag{2.2}$$

$$P_{over} = \sum_{t} slk_{pos} * I_{over} \tag{2.3}$$

The main decision variable in this optimization is $x_{p,t}$. The optimizer changes the power output of each plant in order to minimize cost. Each cost is directly related to the power output. The power outputs are constrained by their ramp rates, Equation 3.1 and 3.2, and the minimum and maximum generation, Equation 3.2 and 3.3.

$$x_{p,t} - x_{p,t-1} < 60(\delta_p \Delta t) \tag{3.1}$$

$$x_{p,t-1} - x_{p,t} < 60(\delta_p \Delta t) \tag{3.2}$$

$$x_{p,t} \geq x_p^{min} \tag{3.3}$$

$$x_{p,t} \leq x_p^{max} \tag{3.4}$$

Equation 3.1 and 3.2 multiply the ramp rate by 60 so that the time step, Δt, is on the order of minutes, like that ramp rate, δ_p. Equation 3.3 and 3.4 ensure that the power generation is within appropriate plant limits.

Optimization Results and Discussion

The first task of this optimization was to model the economics of a power grid running over a one week period. The grid consisted of 10 aggregate plants representing the entirety of the ERCOT interconnection. Load and wind data are also from ERCOT. The optimizer's responsibility was to find the cheapest mix of generation for the given week while still meeting load. This is shown in Figure 1.

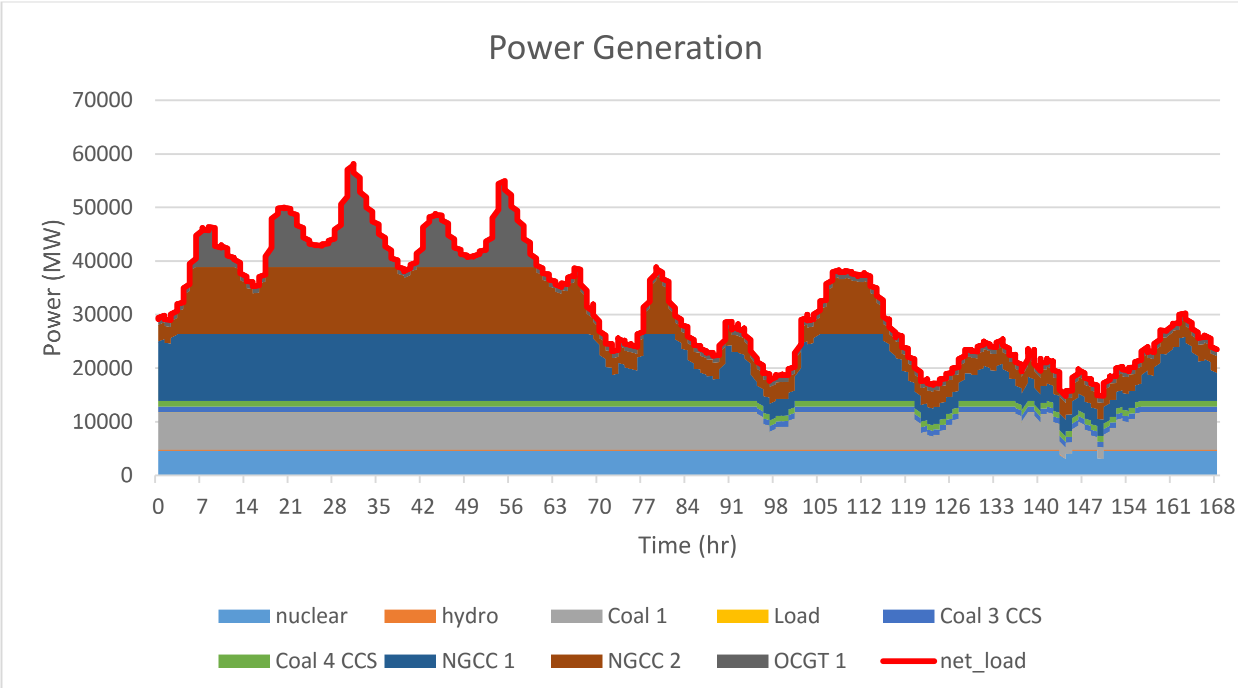

Figure 1 Power generation for 7 days with 2 Cryogenic Capture plants.

The load that the optimizer is required to meet is a net load, meaning that the wind energy is subtracted from the actual load at the onset. This represents a situation in which all wind energy has to be used. This is a fairly realistic situation, as many utilities are requiring the use of renewables. The peaks at the end of the week are so much lower because there is much more wind generation. The first plants to change in load are the open cycle gas turbines (OCGT), followed by natural gas combined cycle (NGCC) and hydro, then coal, and lastly nuclear. This is why OCGT and NGCC are utilized quite a bit more at the front end of the week when load is high. Because this is a unit dispatch models that assumes plants are always committed, or generating power, the points with the smallest load see coal and nuclear ramp down. In reality, some units would be taken offline in order to avoid this situation.

This model also helps provide a comprehensive economic analysis. A comparison of operating cost, CO_2 emissions, and cost of generation penalties is itemized in Table 3**.** This is with a modest CO_2 tax of \$35/tCO_2. Carbon Capture eliminates 90% of the CO_2 from two of the coal plants in the grid. As more CCC is added, or the carbon tax increases, the CCC becomes more appealing economically.

Table 3 Comparison with and without CCC

	With CCC	Without CCC
Total Cost (\$)	\$ 280,431,288.73	\$ 1,291,228,694.61
Over/ Under Production Penalty (\$)	\$ 0	\$ 93,297,049.24
CO_2 Produced (Ton)	428,938,535.94	1,072,076,712.56

Another piece of CCC functionality that was analyzed was energy storage. By time-shifting the parasitic load from refrigerant production, the system allows for greater flexibility in production. This trend is seen in the penalty pricing in table 2. Because CCC could time shift the parasitic load to off peak times. This allowed for more flexibility within hydro and natural gas peaking units and money could be save. This is especially important where wind is high and at off peak times.

One advantage, as shown by the penalty cost of zero, is increase flexibility. Figure 2 shows the amount the net load from customers, and coal generation minus CCC demand. The CCC load demand decreased when demand was high and increased when demand was low, even though the power output was constant from the coal plant. The storage is usually increasing before towards minimum loads and is used up at times near peak load. This let the coal plant load follow, even though it is not normally equipped to do so.

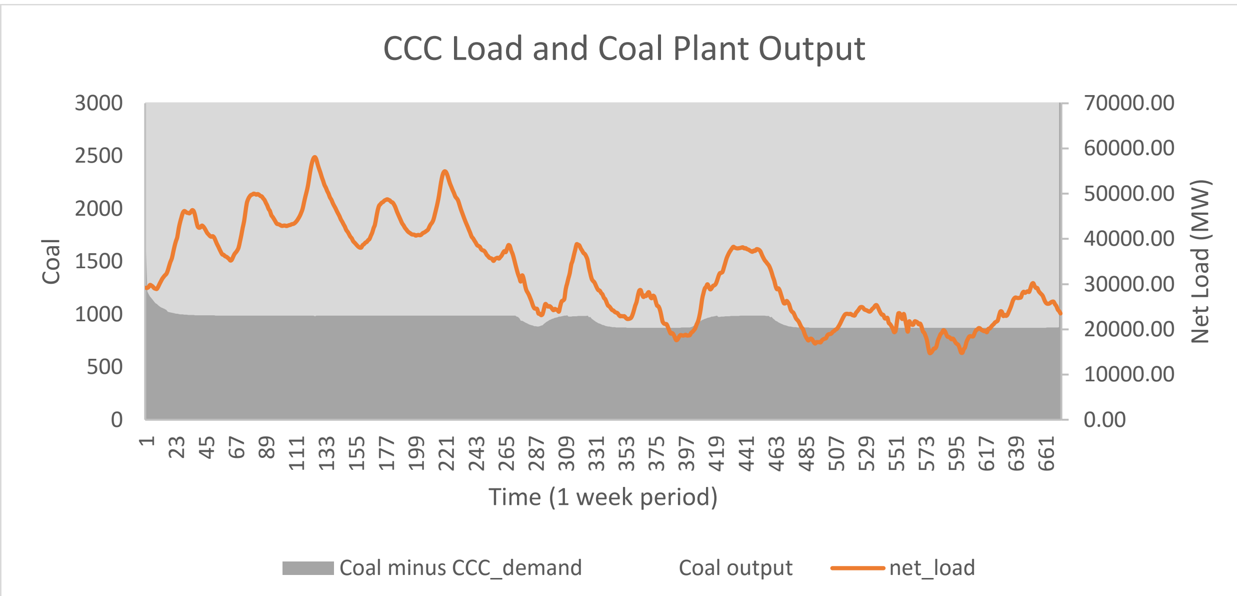

Figure 2 CCC Load with Coal Plant Generation

Conclusion

The dispatch model showed the usefulness of CCC. In economic environments that place an emphasis on carbon free generation, CCC becomes a viable option. Even with a $35/t$CO_2$ tax, the cost savings over one week were just under 1 billion dollars. This savings will only increase in more carbon-regulated environments. This analysis also demonstrated the CCC system's ability to increase grid flexibility. The system also show great flexibility in load following.

Future work should include an analysis of ancillary services and unit commitment. It would also be beneficial to model scenarios with large amounts of wind energy (two to five times the amount currently modeled). This would give further insight into how the system does with intermittent renewables. Other work could compare the CCC system to other types of carbon capture or storage on a grid scale.

Acknowledgements

The authors would like to thank Wesley Cole, Mostafa Safdarnejad, and John Hedengren for their mentoring and assistance in this project.

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