Reduction in Cycling of the Boilers by Using Large-Scale Energy Storage of Cryogenic Carbon Capture

Seyed Mostafa Safdarnejad

J. D. Hedengren

L. Baxter

Chemical Engineering Department

Brigham Young University

With the continuing increase in electricity consumption and penetration of renewable energy, power grids will require more responsive power generation units. When electricity demand is high or when renewable energy sources have high fluctuations, reliable power sources should be used to meet the demand and compensate for the fluctuations in the renewables. This becomes especially important for some of the renewables such as wind and solar that are very intermittent. In such events, two main approaches are used to meet the power demand or compensate for the fluctuations: (1) using responsive power generation units such as gas- or oil- fired turbines (2) cycling the baseline generation units in advance. However, running gas- or oil-fired turbines (as the spinning/non-spinning reserves) is very expensive and inefficient. Cycling the baseline generation units, such as coal-fired boilers, also imposes various thermal damage to the boilers [1]. A third approach to overcome the abovementioned problems is to use large-scale energy storage systems. Energy storage offers several advantages to the power generation units. The most important function of the energy storage is the peak-shaving of the electricity load. This means that whenever power could be produced in excess, it is generated and saved in an energy storage medium. Then, during periods with high electricity demand, stored energy is used to meet the demand. When energy storage is used, the baseline power generators are not obliged to cycle to meet the peak demand. In addition, by appropriately designing an energy storage system, there is less need for the responsive but expensive generators (spinning/non-spinning reserves) because the required electricity during peak hours is met from the energy storage. Other advantages of the energy storage systems include the ability to have energy arbitrage, the possibility to smooth the variations in renewable energy sources and to increase their contribution to the grid, and power grid stability [2].

Different energy storage systems have been considered in the literature. The most widely applied technologies for energy storage are batteries, compressed air energy storage (CAES), pumped hydro-electricity energy storage (PHES), and thermal storage [3]–[5]. CAES and PHES are 56-85% efficient; however, they have specific geographical requirement that limit their applicability. Batteries are very efficient (90%) and have fast response to load changes and do not have geographical limitations but they are expensive [6]. In this study, thermal energy storage, offered by Cryogenic Carbon Capture ™ (CCC) [7], is used for integration with power generation units. The energy storage offered by the CCC process is +95% efficient and it does not have the geographical limitations mentioned above [6]. The cost of the energy storage system of the CCC process is also small compared to the constructional cost of the CCC process. The economic benefits of the energy storage of the CCC process is high enough that it can recover a significant fraction of the cost of construction of the CCC process [8].

Cryogenic carbon capture is a new technology for the separation of CO_2 from flue gases generated by the power plants. CO_2 is removed from the flue gas by cooling the gas down to a temperature below the desublimation point of the CO_2. Solid CO_2 is then separated from the slurry by using filters [6], [9]. The cooling medium for the separation is provided by two refrigeration cycles. CF_4 is used as the refrigerant in one of the cycles while liquefied natural gas (LNG) is used in the other one. These refrigeration cycles consume the most energy. The energy storage, however, provides the flexibility to produce LNG in excess when electricity demand is low or when renewables are available. Overproduced LNG is then stored inside a well-insulated tank. During periods with high electricity demand, LNG is recovered from the tank and is used in the CCC process. Using stored LNG leads to significant reduction in the power consumption of the refrigeration cycles. This means that more power is available for the grid during peak hours. In addition, LNG is vaporized after removing heat from the CCC process and the vaporized LNG is used for power production in a gas turbine [10]–[12]. The power produced from the gas turbine can be used to meet the power demand of the CCC process as well as the residential demand. In addition, by producing gas power from the stored LNG, it is possible to keep the baseline power unit from cycling and avoid running the spinning/non-spinning reserves when there is a peak electricity demand or high fluctuations in renewables. The possibility of producing power in a gas turbine and the reduction in energy consumption of the CCC process during peak hours are both the features that are offered by using an energy storage system. The significance of the energy storage becomes of great importance when the regulations for the CO_2 emissions of the power plants become effective in near future.

In a recent study, integrating the CCC process and the associated energy storage system with a single load-following power generation unit was studied [8], [12]. In this study, no cycling cost was assumed for the load-following boiler but the rate of change for the boiler power output was limited to 7%/min. This study represents the recently designed power generation units with load-following capability. However, there are still many baseline power generation units. In the current study, the impact of using the CCC process and the associated energy storage on a baseline coal-fired generation unit (1800 MW) is considered. Gas turbine (fed from the vaporized LNG also recovered from the energy storage) is able to produce up to 1000 MW power while the maximum wind power output adopted in this study is 390 MW. Maximum residential demand is also 2000 MW. The performance of the hybrid system of baseline power generation unit and the CCC process shows that by using the energy storage, the power output from the boiler is kept at the baseline value. Total power demand is met by using a combination of power production from steam boiler, gas turbine, and wind. All of the available wind power is also utilized in meeting the electricity demand. As for the load-following case, reduction in the power consumption in the refrigeration cycles is another important conclusion from this investigation.

As a second case study, leveling the fluctuations in the power output from a load-following boiler is considered. In this case, the boiler can have unconstrained fluctuations in the power output; however, a cycling cost is considered for each load-following event. This case study represents a more realistic operational strategy compared to the previous study in [8]. For a case study with energy storage, it is seen that dedicating a cycling cost to the movement in boiler power output results in significantly lower fluctuations in the boiler power output. Considering an appropriate size for the energy storage as well as the cycling costs for the boiler lead to minimal cycling in the boiler power output, even in the event of a sudden increase in power demand. As mentioned before, the power provided by the gas turbine is used to meet the peak electricity demand without needing to frequently cycle the boiler. Supplying power from the gas turbine is a direct result of using energy storage. The long-term results of having less cycling in the boiler power output are the longer lifetime and lower maintenance costs of the boiler. In addition to the saving in the capital and maintenance costs of boiler, significant saving in the operating cost of the power plant with energy storage is observed. Without energy storage, the power generation unit has to meet the demand by running the spinning/non-spinning reserves. Energy storage reduces the need for running the spinning/non- spinning reserves which significantly reduces the operational costs.

[1] N. Kumar, P. Besuner, S. Lefton, D. Agan, and D. Hilleman, “Power Plant Cycling Costs,” 2012.

[2] S. M. Safdarnejad, J. D. Hedengrena, and L. L. Baxter, “Effect of Cryogenic Carbon Capture (CCC) on Smart Power Grids,” in *American Institute of Chemical Engineers (AIChE)*, 2015.

[3] J. Nease and T. A. A. II, “Coal-fuelled systems for peaking power with 100% {CO2} capture through integration of solid oxide fuel cells with compressed air energy storage,” *J. Power Sources*, vol. 251, no. 0, pp. 92–107, 2014.

[4] D. Connolly, H. Lund, B. V Mathiesen, E. Pican, and M. Leahy, “The technical and economic implications of integrating fluctuating renewable energy using energy storage,” *Renew. Energy*, vol. 43, no. 0, pp. 47–60, 2012.

[5] K. M. Powell, J. D. Hedengren, and T. F. Edgar, “Dynamic optimization of a hybrid solar thermal and fossil fuel system,” *Sol. Energy*, vol. 108, no. 0, pp. 210–218, Oct. 2014.

[6] M. Jensen, “Energy Processes Enabled by Cryogenic Carbon Capture,” Brigham Young University, 2015.

[7] “Sustainable Energy Solutions Company.” [Online]. Available: http://sesinnovation.com/.

[8] S. M. Safdarnejad, J. D. Hedengrena, and L. L. Baxter, “Plant-level Dynamic Optimization of Cryogenic Carbon Capture with Conventional and Renewable Power Sources,” *Appl. Energy*, vol. 149, pp. 354–366, 2015.

[9] M. J. Jensen, C. S. Russell, D. Bergeson, C. D. Hoeger, D. J. Frankman, C. S. Bence, and L. L. Baxter, “Prediction and Validation of External Cooling Loop Cryogenic Carbon Capture (CCC ECL) for Full-Scale Coal-Fired Power Plant Retrofit,” *Int. J. Greenh. Gas Control*, p. accepted, in progress, 2015.

[10] L. Baxter, “Carbon Dioxide Capture from Flue Gas,” App. 12/745,193, 2011.

[11] L. Baxter, “Systems and methods for integrated energy storage and cryogenic carbon capture,” WO Patent App. PCT/US2012/061,392, 2013.

[12] S. M. Safdarnejad, L. Kennington, L. Baxter, and J. Hedengren, “Investigating the Impact of Cryogenic Carbon Capture on the Performance of Power Plants,” American Control Conference (ACC), Chicago, IL, 2015.