Dynamic Optimization of Cryogenic Carbon Capture with Large-scale Adoption of Renewable Power

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An increase in energy demand and concerns over the global greenhouse emissions have led researchers to pursue other sources of energy like wind and solar which are clean and renewable. While developing renewable power sources is helpful in reducing the greenhouse emission, the intermittent and non-dispatchable nature of these generation sources present challenges [1]. Thus, they must be integrated with other power sources, usually fossil fuel, to establish a reliable power generation unit [2]. By using an energy storage system, however, the renewable power can be stored when it is available and utilized at a later time. Then, when renewables are not available for power generation (e.g. cloudy days for solar power and calm time for wind power), the stored energy can be released to overcome the power shortage [1]. Using the storage system leads to significant fuel cost reduction when there is a high adoption of renewables, as the renewable energy can be stored and better offset combustion of fossil fuels [3]. This study optimizes power plant operations to best utilize scalable energy storage for increased adoption of renewable power sources and enhanced performance of the power generation.

As mentioned previously, CO_2 emission regulations from fossil-fuel combustion are becoming stricter; thus, different CO_2 capture methods are being explored [4-7]. However, the major drawback of most of the CO_2 removal systems is the parasitic load of the process, especially of concern during peak demand periods when excess generation capacity is not available. Thus, it is important to develop new CO_2 capture processes with lower parasitic load. Cryogenic Carbon Capture (CCC) is a post-combustion technology with low parasitic load (12-18%) [8]. In this process, CO_2 is captured in the flue gas through desublimation [9, 10]. The CCC process also has energy storage capability which makes it a promising technology to integrate energy storage at the grid scale with existing fossil fuel power plants [11]. The proposed energy storage is scalable to large scale systems.

The energy required to run the compressors for the refrigeration cycles is the significant portion of the energy consumption of the CCC. However, in the energy storage version of CCC (ES-CCC), excess energy production is stored in the form of a refrigerant. During peak hours, the parasitic load associated with running the refrigeration compressors is decreased by replacing them with the stored refrigerant. This means that during peak hours, refrigerant production rate decreases which in turn decreases the energy demand required by the CCC. The energy recovery mode can last for as long as the stored refrigerant is available.

The CCC process is considered a rapid load changing process because all of the main components such as compressors and heat exchangers have fast start-up times [12]. This rapid response along with the storage capability allow for integration of conventional thermal power generation units with renewable intermittent power plants. Therefore, integration of power generation units (including coal, gas, and wind power) with CCC process is considered in this study as a viable grid-scale energy storage mechanism that allows better utilization of renewable energy sources. While there is a wide body of research focusing on developing the CO_2 removal system and investigating its impact on power generation systems, most of it considers chemical absorption with amine [13-14]. The simulations are also mostly implemented for the steady state case [15-16]. In this investigation, dynamic simulation and optimization of the integrated systems are considered which allows for time-shifting of the parasitic load of the carbon mitigation process. Furthermore, the impact of the transient nature of the renewable power sources is considered with dynamic optimization. The profit of the integrated power generation and ES-CCC system is maximized while meeting the residential and CCC electricity demands. The variation of coal power is minimized to avoid severe thermal cycling damage to the boilers due to frequent load changing. This study uses ℓ_1 – norm with a dynamic model that is solved with Non-Linear

Programming (NLP) techniques [17]. After orthogonal collocation on finite elements to convert from a Differential Algebraic Equation (DAE) to NLP, the model includes 4536 variables and 4320 equations and is solved using a simultaneous optimization with the APOPT solver [18]. APMonitor modeling language [19] is used in this study to formulate the problem. The CPU time and number of iterations required to obtain a successful solution is less than 7 seconds and 6 iterations, respectively.

This analysis demonstrates that a combination of coal, gas, and wind power meets the total electricity demand (residential and CCC demands). During off peak hours, the refrigerant production rate increases and it decreases during peak hours as it takes part of the required refrigerant from the storage vessel. The level of the refrigerant in the vessel also shows inverse cycling with the electricity demand curve; when power generation is more than electricity demand, the refrigerant level increases and when it is less, it decreases. Thus, the proposed system fulfills storage by time-shifting the parasitic load of the CCC process and better utilizing renewable power sources.

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