The economic value of flexible CCS in net-zero electricity systems: The case of the UK

EPRG Working Paper 2308

Cambridge Working Paper in Economics 2336

Chi Kong Chyong, David M Reiner, Rebecca Ly, Mathilde Fajardy

The increasing use of variable renewable energy (VRE) for deep decarbonisation of power grids will constrain the electricity system due to its intermittent nature. The integration of VRE is closely linked to the flexibility of the electricity system and other generators. To ensure the security of supply sufficient to meet intra-day demand variations, dispatchable fast ramping technologies are necessary. To support the massive rollout of VRE, flexible solutions, such as carbon capture and storage (CCS) paired with either natural gas or bioenergy (BECCS) and electrical storage technologies, such as lithium-ion batteries, have been discussed. However, the incentives to deploy flexible CCS on a gas plant will depend on the long-term evolution of the electricity price, its volatility and policy support measures, such as carbon price.

For instance, deploying CCS will be more profitable with a higher carbon price. However, there may be hours when electricity prices are high relative to the cost of carbon emissions due to scarcity events caused by high demand and/or low wind and solar electricity generation. During such hours, the incentives to capture CO_2 emissions will be lower. The deployment of flexible CCS on gas plants can play a significant role in supporting the integration of VRE and achieving deep decarbonisation goals.

Thus, the ability to maximise profits within the day lies in the CCS unit's capability to operate when electricity prices are low and switch off when electricity prices are high. If carbon prices are sufficiently low, the CCGT will vent the generated CO_2 when electricity prices are high. If carbon prices are high, the CCGT power plant will reduce its output to allocate electricity to CCS operations.

The ability to store CO_2 can also play an important role. The electricity penalty of flexible CCS can be shifted from periods of high electricity prices by storing the generated CO_2 to off-peak periods when electricity prices are lower. In short, having a dedicated CO_2 storage tank at the power plant fitted with CCS allows temporal arbitrage between low and high electricity price periods.

This switching ability is especially valuable as carbon price rises and electricity prices become more volatile. The CCGT can then capture extra profits by dispatching electricity instead of allocating the production to run the CCS plant. The additional profit generated during these peak price hours increases with the level of electricity prices given constant within-day short-run marginal costs (e.g., fuel and carbon prices).

In this paper, we study the flexible operations of CCGT-CCS using an hourly plant-level unit commitment electricity production cost minimisation model to demonstrate the economic value of having a flexible CCS power plant. By exploring flexible CCS with storage, we allow CCS to be decoupled from the CCGT power plant in its operations. In this respect, a CCGT-CCS plant can maximise its profits by comparing its short-run marginal cost (SRMC) of CCGT (fuel and carbon costs and variable running costs) to hourly electricity prices. At the same time, the CCS unit minimises its auxiliary electricity penalty (electricity consumed to run the carbon capture process at the CCGT-CCS plant) during the day. We expect that the volatility of electricity prices plays a vital role in generating additional profit streams from flexible CCS operating in systems with large shares of variable renewables, thus justifying running CCGT-CCS in a flexible rather than in a baseload mode.

Our modelling results highlight the importance of flexible capture to the viability of CCS, regardless of the type of flexible post-combustion carbon capture technologies (variable capture or storage). Our model captures two arbitrage decisions: the decision to either vent the flue gas or to capture it. When the flue gas is captured, the decision is to either regenerate the solvent or store it for later regeneration. These two trade-offs vary with two critical inputs: the carbon price level and the intraday variation in electricity price.

Thus, first, we found that increasing carbon price encourages the use of full carbon CO_2 capture (i.e., at the 90% design rate) as soon as the operational cost of CCS – made up of the electricity price and the cost of transport and storage – becomes sufficiently low compared to the carbon price. This trade-off is reflected in the modelling output, where the effective carbon capture rate rises from 2030 through 2050 due to the increasing carbon prices over this period. This finding is in line with previous estimates in the literature.

Second, the main contribution of our case study remains in the insights gained from exploring solvent storage dynamics at higher temporal resolution. Flexible carbon capture does not force the rich solvent (CO_2-loaded solvent) to be regenerated within an hour, i.e., as soon as the flue gas enters the CCS. Since the opportunity cost of carbon capture is the auxiliary electricity penalty, flexible carbon capture allows the rich solvent to be stored in a tank during peak hours and regenerated when electricity prices are lower. Storage enables the intertemporal arbitrage of electricity usage that eventually increases the profitability of the CCGT-CCS plant: the rich solvent does not have to be regenerated instantaneously but can be stored instead so that more electricity is dispatched and sold at peak-hour prices. In the net-zero scenarios, the significant shares of intermittent renewables will increase the volatility of electricity prices because of higher spikes during peak hours when the capacity margin is reduced and low (or negative) electricity prices during off-peak hours with electricity surpluses. Despite the deployment of significant electricity storage capacity, the greater volatility of electricity prices in the following decades is expected to lead to a more profitable intertemporal arbitrage between peak and off-peak hours.

A high carbon price is necessary if the UK wants to deploy fossil power plants with CCS profitably: higher prices encourage the uptake of CCS as it becomes more profitable to capture the flue gas from the power plant rather than venting it. While there is little doubt that deploying CCS technologies relies on an increasing carbon price in the long run, the impact of a carbon price on the present value of CCGT-CCS is more nuanced. The plant's profit margin and investment case will be reduced if the carbon price is too high. This effect is significant as we phase out fossil-fuel-based generation because as fossil fuels disappear from the system, the high carbon price will not translate into high electricity prices (carbon price being part of fossil plant's marginal cost). Our modelled Leading the Way (LW) scenario is a clear example of this: the LW scenario has almost no fossil-fuel-based generation. Therefore, even a very high carbon price will not have much effect on electricity price. Thus, for the market setup envisaged by the LW scenario, investment in CCS will be feasible only in an extremely high electricity price volatility environment.

Thus, in this context of decarbonisation, the volatility of electricity prices resulting from the deployment of large shares of renewables and expanding storage capacity will necessarily impact the marginal profit of fossil peaking plants which will be able to ramp up during peak hours to meet the electricity demand. By allowing the carbon capture unit of fossil plants to be flexible with solvent storage, the operating profit is improved during peak hours since the postponed electricity penalty to off-peak hours when the electricity price is lower.

As a result, the economic value of solvent storage is to take the potential advantage of increased price volatility – under higher electricity price volatility assumptions, the NPV of investing in the solvent storage would be positive, ranging from £5.3M-£8M. This represents a total return on investment (ROI) of 66-101%. In relative terms, this is much higher than the total ROI of the CCGT-CCS plant alone (12-45%). Thus, investing in solvent storage to allow further flexibility for the plant operation has a non-negligible return on investment – it delivers highly positive economic value under volatile electricity prices.

While there is an economic case for investing in flexible CCS with solvent storage for individual operators, the benefits of the solvent storage flexible solution should be seen in the context of the overall system ‘flexibility’ requirements of a low-carbon power system. An investment of £8M allows the plant to add additional flexibility of 112MW of low-carbon generation capacity, or £70/kW. This investment would only be a fraction of the capital costs needed for “mainstream” energy storage technologies, such as lithium-ion batteries (~£200/kW), compressed air energy storage (CAES) (~£800/kW), or hydro-pumped storage (~£1,200/kW).

To summarise, the advantage of using CCS with solvent storage as a flexible solution to support the massive roll-out of variable renewable energy (VRE) is not just increased profitability. Unlike other storage technologies, the advantage of this additional capacity is its *firmness*, meaning that it does not need to be charged first to produce energy, making its production decision independent of such considerations. The carbon intensity of energy production from storage is a function of the average carbon intensity of the power system itself. Still, the solvent storage solution provides extra flexible production capacity at very low-carbon intensity. The firmness of the solvent storage solution should also be seen in the context of the inter-seasonality of energy production and demand (that is, the need for very long-duration storage). Flexible CCS with solvent storage can act as a hedge against sudden changes in electricity balance at peak times and provides an option for taking advantage of sudden price spikes.

Contact	kc3634@columbia.edu
Publication	April 2023
Financial Support	N/A