Indicative Energy Technology Assessment of Natural Gas-Fired Power Plants with Carbon Capture and Storage: A UK Perspective

Samuel J. G. Cooper, Angelos Evangelou, and Geoffrey P. Hammond

Abstract—An indicative energy technology assessment of carbon capture and storage facilities coupled to natural gas combined cycle power plants has been undertaken. Comparisons of carbon capture and storage equipped power plants are reported in terms of their energy, environmental, and economic performance with the aid of several influential international studies. The 1200 MW Saltend Power Station was used as a case study of a typical potential UK-based carbon capture and storage equipped power plant. Post-combustion capture technologies were analysed with realistic, clustered transport pipelines to a depleted gas field in the North Sea.

Keywords—Carbon capture and storage (CCS), Economics, Electricity generation, Energy requirements, Natural gas-fired power plants

I. INTRODUCTION

CARBON capture and storage (CCS) is an important, 'transitional' component of a wider low carbon strategy for the future in the industrial world [1]. Such facilities, coupled to fossil-fuelled power plants or industrial sites, provide a climate change mitigation strategy that potentially permits the continued use of fossil fuel resources, whilst reducing the carbon dioxide (CO_2) emissions to the atmosphere [2,3]. Industrial companies have argued that, in the United Kingdom (UK), CCS equipped power stations might only be built using natural gas combined cycle (NGCC) power plants, because of their lower capital cost compared to supercritical coal plants (especially as such plant might operate at 'mid-merit', rather than as baseload).

In this study, an indicative energy technology assessment of CCS equipment coupled to a NGCC power plant has been undertaken. Comparisons of NGCC-CCS facilities in terms of their energy and economic performance are reported with the aid of several influential international studies. The 1200 MW Saltend Power Station, near Hull in the North East of England, was then used as a case study of a typical UK-based NGCC-CCS plant. Post-combustion capture technologies were analysed with realistic, clustered transport pipelines to a depleted gas field in the North Sea.

The present contribution is part of an ongoing research effort aimed at evaluating and optimising the performance of energy systems, together with transition pathways towards a low carbon future. It builds on earlier studies of the thermodynamic (including 'exergoeconomic') and techno-economic analysis of power plants with and without CCS by Hammond and Ondo Akwe [4], Hammond *et al*. [5], and Hammond [6]. Although the focus in the present work is the UK context, the findings have broader implications for the adoption of clean power technologies from an international perspective. It is 'indicative' in the sense of being a simplified evaluation and illustration of the performance of state-of-the-art CCS systems. Nevertheless, such assessments provide a valuable evidence base for developers, policy makers, and other stakeholders.

II. CARBON CAPTURE TECHNOLOGIES

There are three main methods for capturing CO2 from power stations that are currently in development: post-combustion capture, pre-combustion capture, and oxy-fuel combustion capture.

Post-combustion capture typically uses chemical solvents such as mono-ethanolamine (MEA) to absorb CO_2 from the exhaust (flue) gas after combustion. This is the most common method of capture but the low concentration of CO_2 in the flue gas necessitates powerful chemical solvents and large-scale equipment. It is a costly and energy intensive process but offers potential for retrofitting and was therefore favored by

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the UK Government [5].

Pre-combustion capture separates CO_2 from the gas stream before combustion, where the higher concentration of CO_2 aids the capture process and enables less selective capture techniques, such as absorption using 'Selexol'. The quantity of gas involved is lower, reducing the energy requirements and the need for large equipment, but the process involves more drastic changes to the power station [3,5,7,8].

Oxy-fuel combustion capture involves combustion of fuel in oxygen instead of air. This produces CO_2 rich exhaust but is expensive, and presently only at the demonstration phase. Research is currently examining more effective chemical and physical absorbents, as well as the development of novel capture techniques. The latter include new membranes and cryogenic techniques that may lower the costs and energy penalties associated with carbon capture [3,5,7,8].

Storage can be geological, oceanic, in ecosystems, in solid carbonates, or in industrial products. Geological storage is currently the most viable option in the UK context [5,6]. Depleted oil and gas reservoirs, deep saline formations, and depleted coal seams are available. The CO_2 storage capacity in North Sea depleted oil and gas reservoirs is estimated to be around 10,000 $MtCO_2$ [9], equivalent to 60 years of current emissions. This is complemented by a further 14,000 $MtCO_2$ of storage capacity in UK saline aquifers [9]. Enhanced Oil Recovery (EOR) involves the injection and storage of CO_2 into oil fields that are coming to the end of their useful life [3]. This can generate additional revenue by capturing more oil, delays costly oil field decommissioning, and can utilize the existing infrastructure of the oil well. Enhanced Gas Recovery and Enhanced Coal-bed Methane can also enhance profitability, but might only increase the recovery rate by around 5% compared to levels of 15% for EOR [5].

III. International cross-study comparison

Several recent studies have attempted to quantify the techno-economic performance of CCS facilities utilized in the power sector, although these are still subjected to considerable uncertainties [10-19]. In order to assess these differences a number of selected studies have been reviewed. Criteria were applied in the selection of the studies in order to ensure their relevance. No studies prior to 2007 were considered as construction and operating costs were likely to differ significantly in historic cases. Studies which did not consider the subject in adequate depth or which did not provide adequate information for comparison were also excluded. All of the studies assumed that the post-combustion capture method was used. Studies [10-16] were specific to the US while [17-19] were specific to the UK. The majority of the studies included results for both *first-of-a-kind* (FOAK) and *n*th*-of-a-kind* (NOAK) CCS plants, but for the present purposes only the results corresponding to FOAK estimates are reported here. All efficiencies were based upon the Higher Heating Value of natural gas or were converted to this basis. Capacity factors of 75% [12,13], 80% [9,14,15] or 85% [7,8,10,11] were used in the studies.

The average net efficiency reduction was 7.5 percentage points, with a range from 6.8 to 8.8 (see Fig. 1). The energy penalty is defined as the efficiency reduction relative to the nominal efficiency without CCS; it indicates the relative increase in energy input required by the CCS. Energy penalties ranged from 13.6% to 16.8%, with an average of 14.7%. The majority of the energy penalty was due to two factors. The energy required to provide heat to the regenerator is taken from the steam cycle and accounted for approximately 55% of the observed energy penalties. A further 35% was typically due to the compression of the captured CO_2 for transport [20].

The NGCC plant levelised costs of electricity (LCOE) [5] are shown in Table I. The average increase is 35 $\$_{US2013}$/MWh, when CCS is adopted, with a range from 16 to 51 $\$_{US2013}$/MWh.

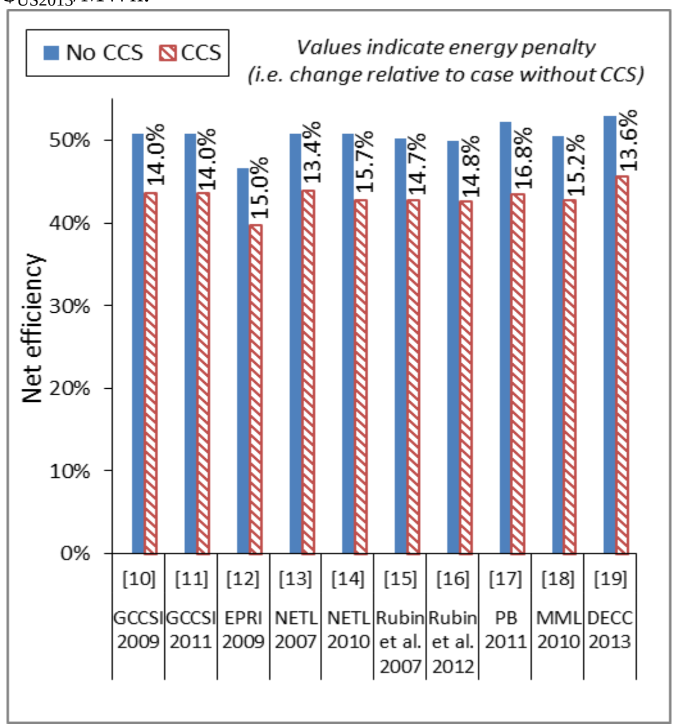

Fig. 1 Performance impact of CCS. Data adapted from [7-16]

TABLE I
COMPARISON BETWEEN COST PROJECTIONS (CONVERTED TO $US2013/MWH)

Study	NGCC	NGCC-CCS	Increase	
GCCSI 2009	84	121	37	[10]
GCCSI 2011	94	131	37	[11]
EPRI 2009	74	102	28	[12]
NETL 2007	77	109	32	[13]
NETL 2010	84	122	38	[14]
Rubin 2007	72	109	37	[15]
Rubin 2012	68	95	27	[16]
PB 2011	121	166	45	[17]
MML 2010	127	178	51	[18]
DECC 2013 (2019 build)	133	148	16	[19]

Several factors contribute to the variation in costs, including fuel costs, operating assumptions and capital costs. An increase in fuel costs (from 6.1 \$/MWh to 7.0 \$/MWh) was the main reason for the increase in the LCOE observed between the GCCSI reports [10,11], despite more arduous transport requirements being assumed in the earlier study. Higher fuel prices are one of the causes for the increase in LCOE observed in the studies based in the UK [17-19] relative to those based in the US. EPRI [12] calculated that the LCOE of the NGCC-CCS would increase by 33 $\$_{US2013}$/MWh if the capacity factor dropped from 80% to 40%. The effect was less significant (22 $\$_{US2013}$/MWh) for conventional NGCC plant. The main difference in the LCOE calculated by the two NETL studies [13,14] is due to different assumptions regarding capital costs.

Although a carbon capture rate of approximately 90% is generally assumed or calculated in these studies, it should be noted that the impact of upstream emissions from the production and transport of natural gas are likely to reduce the overall greenhouse gas (GHG) emissions saving to around 70% [21,22].

IV. Case Study Of CCS In The UK

In order to better understand the performance of the technology, a modelling approach was employed based upon Saltend NGCC power station in the UK. Built in 2000, Saltend power station uses three 701F2 Mitsubishi Heavy Industries gas turbines in a single shaft combined cycle configuration, each with a three pressure level vertical Heat Recovery Steam Generator and a reheat steam turbine (see Fig. 2).

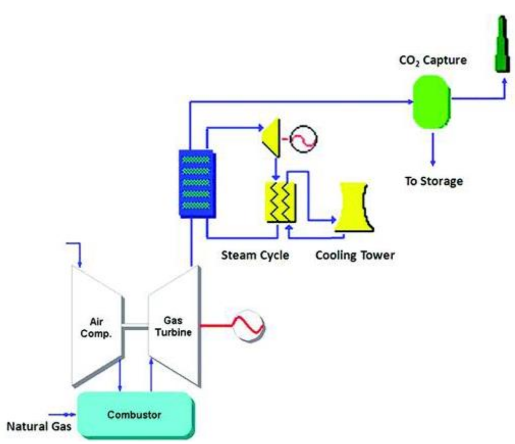

Fig. 2 Modelled plant configuration

It has a net power output capacity of 1177 MWe. The relatively large capacity and low emissions are representative of the characteristics of newer NGCC plants that are likely to be targeted for use with CCS [23]. It is located within the Yorkshire and the Humber Cluster which is the biggest CO_2 source cluster in the UK. Post-combustion capture using Fluor's Econamine FG+ technology was assumed. Analysis of the potential locations for CO_2 storage resulted in an estimate of 250km total pipeline distance, of which around 30km was overland with flat terrain. Modelling was repeated with carbon prices of 23.7 $\$_{US}/t_{CO2}$ (consistent with the UK carbon floor price) and 83 $\$_{US}/t_{CO2}$ (consistent with the average used in Ref. [17,18]).

The *Integrated Environmental Control Model* (IECM version 8.0.2), developed by Carnegie Mellon University for the US *National Energy Technology Laboratory* (NETL), modelled the economic and performance data for the power plants and CCS equipment. IECM has been widely used in connection with US studies (e.g. [15,16]) and by Hammond *et al.* [4,5]. The use of IECM ensured an adequate degree of detail and broad analysis.

The main technical and economic performance characteristics of the case study are summarized in Table II, for both the reference case and the one with CCS. The use of CCS reduces the efficiency by 7.3 percentage points, incurring an energy penalty of **14.5%**. This is close to the average of the energy penalties shown in Fig. 1. The operational emissions rate decreases substantially with the addition of CCS. The percentage reduction is 88%; close to the rated capture efficiency (90%) of the system.

Table II
Case study main technical and economic performance characteristics

Parameter	Reference NGCC		NGCC with CCS	
Net Power Output [MW]	1125		961	
Net Plant efficiency [%]	50.3		43	
Energy Penalty [%]	-		14.5	
Emissions rate [t_{CO2}/MWh]	0.4		0.047	
Levelised Cost of Generation [$\$_{US2013}$/MWh]	65.8		72.8	
Levelised Cost of Separation &Capture [$\$_{US2013}$/MWh]	0.0		16.1	
Levelised Cost of Transport & Storage [$\$_{US2013}$/MWh]	0.0		3.6	
Carbon price:	Standard	High	Standard	High
Levelised Cost of Carbon [$\$_{US2013}$/MWh]	9.8	34.5	1.1	4.0
Total LCOE [$\$_{US2013}$/MWh]	75.6	100.3	93.7	96.5

CCS increases the LCOE by 23.9% (18.1 $\$_{US2013}$/MWh) under the standard carbon price assumption but slightly decreases it if the high price is used (by 3.8%, 3.8 $\$_{US2013}$/MWh). The CCS equipment increases the capital costs by around 93% but the majority of the generation cost increase is due to the cost of the fuel.

Fuel prices prevalent in the UK in 2013 would increase the LCOEs by 4.4 and 4.8 $\$_{US2013}$/MWh for the non-CCS and CCS cases respectively. The results are relatively insensitive to the length of pipeline assumed with an range of only 2.5 $\$_{US2013}$/MWh associated with varying the length from 100 km to 400 km. Decreasing the capacity factor of the plant from 85% to 75% is likely to increase the LCOE by around 1.8 and 4 $\$_{US2013}$/MWh for the non-CCS and CCS cases respectively. Taken together, these adjustments suggest that the increase in

LCOE due to CCS may be just under **21 $\$_{US2013}$/MWh** (with standard carbon price), to a total of **102.5 $\$_{US2013}$/MWh**.

This is lower than the LCOEs presented in Table I, apart from for Ref. [16]. Studies [10,11,17-19] assume the use of MEA rather than Ecoamine FG+. Rubin and Zhai [16] suggest that Ecoamine could be economically superior to the standard MEA scrubber methods. It is likely that the use of MEA would increase the LCOE modelled here by around 6.5 $\$_{US2013}$/MWh but this does not fully explain the discrepancy.

The CCS Cost Reduction Task Force (CCRTF) [24] has identified cost reduction opportunities in: (i) transport and storage scale and utilization, (ii) improved 'finance-ability' for the CCS supply chain, and (iii) improved engineering designs and performance. It is likely that the differences between reviewed LCOE estimates and those modelled in this study relate somewhat to these, with underlying assumptions regarding discount rates for capital equipment and the relative maturity of the technologies. Because of this, it may be that the costs generated in this study underestimate UK conditions.

V. Conclusions

An indicative energy technology assessment of NGCC-CCS power plants has been undertaken. A cross-comparison between reputable international studies indicated that CCS can reduce operational (or 'stack') NGCC emissions by up to 90%. However, it should be noted that upstream emissions reduce this GHG saving to only around 70%. An energy penalty of 14% to 17% is associated with the CCS process across these studies. The additional costs of capture, transportation and storage cause an average LCOE increase of 35 $\$_{US2013}$/MWh. A case study was used to investigate a typical UK-based NGCC-CCS plant. Post-combustion capture technologies were analysed with realistic, clustered transport pipelines to a gas field in the North Sea.

CCS currently exhibits a cost premium over its competitors and will rely on cost reduction to become commercially viable. Greater financial incentives for carbon abatement could, in principal, be secured through a higher carbon price from the European Union Emissions Trading Scheme (EU ETS), currently bolstered in the UK by the 'Carbon Floor Price'. Factors that reduce the price of natural gas and that encourage research and development of improved CCS techniques will also improve the case for NGCC-CCS plants. It is possible that the initial deployment of NGCC-CCS plants will be to satisfy base-load demands before cost reductions make operation with a lower capacity factor viable.

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