Interim results from the UK Carbon Capture and Storage Consortium project

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Introduction

The UK Carbon Capture and Storage Consortium Project was started in June 2005 by a group of 14 UK universities and research institutions with funding from the UK Research Councils' Towards a Sustainable Energy Economy (TSEC) Programme. The mission of the consortium is: "to promote an understanding of how options for decoupling fossil fuel use from carbon emissions through the use of carbon capture and storage could be used to assist the UK in achieving an energy system which is environmentally sustainable, socially acceptable and meets energy needs securely and affordably".

Fossil fuels will remain the dominant energy source in the UK for a number of decades and methods to manage the associated carbon emissions are fundamental to the UK's transition towards a sustainable energy economy. Delivering viable large-scale CCS options for the UK demands integrated work by a Consortium of engineering, technological, natural, environmental, social and economic scientists. The Consortium is also a way to rapidly expand a UK research capacity in this area, commensurate with the large potential contributions to national energy targets.

Ongoing work on the potential for carbon (dioxide) capture and storage (CCS) from fossil fuel power stations in the UK suggests that power plants using this family of technologies may be capable of supplying significant amounts of low-emission electricity within one or two decades. If political justification for significant carbon dioxide (CO_2) emission reductions in the UK emerges from global post-Kyoto negotiations, large (~45%) reductions in CO_2 emissions from the UK electricity generation could be achieved as early as 2020.

Potential for CO_2 capture in the UK electricity sector

UEP [1] electricity generation mix figures for 2000–2020 and some alternative scenarios for 2020 are shown in Table 1 [2].

The purpose of these illustrative, scenarios is to indicate electricity sector CO_2 emissions and reliance on gas for three alternative generation mixes, using varying amounts of natural gas (currently a high-price fuel in the UK) and CCS. Small increases in renewable and nuclear generation are also assumed in some cases.

Scenario A shows that a combination of renewables and fuel switching cannot achieve electricity sector emission reductions of more than about 40 $MtCO_2$/yr.

In Scenario B approximately 90% of the projected 2020 coal generation is assumed to be from CCS plants. This appears to be a reasonable target, provided that some existing power plants can be retrofitted with CCS technology. It is also likely that some new integrated gasifier combined cycle (IGCC) plants would be built. In the longer term, additional existing coal power plants may be upgraded to oxyfuel operation or be repowered with gasifiers. Gasifiers with CCS might also be used to supply hydrogen-rich gas from coal, instead of natural gas, to existing combined cycle plants.

Scenario C examines a situation with minimal coal and no new nuclear, and thus increased reliance on gas. CCS is fitted to 13 GW of gas generation, about three quarters of the new natural gas combined cycle (NGCC) build between now (the 2005 value) and 2020.

NGCC plants may also utilise post-combustion CO_2 capture technology or, as in the recently announced Peterhead/Miller project led by BP and Scottish and Southern Energy [3], pre-combustion conversion of natural gas to hydrogen for combustion in a gas turbine, and to CO_2 for storage.

Table 1 UEP electricity generation mix and illustrative alternative scenarios for 2020 [1,2]

	ORIGINAL UEP VALUES					2020 SCENARIOS		
Fuel	Electricity Generation, TWh/yr					A No coal, 20% renew-ables	B 9 GW CCS, 2GW new nuclear	C Less coal, 13GW gas CCS
	2000	2005	2010	2015	2020	2020	2020	2020
Coal	111.9	113	106	89	57	0	7	20
Coal + CCS						0	50	0
Oil	2.1	2	2	2	2	2	2	2
Gas	127	116	132	159	225	264	174	144
Gas + CCS						0	17	100
Nuclear	78.3	84	61	41	27	27	43	27
Renewables	10.1	15	39	58	58	76	76	76
Imports	14.3	9	10	10	10	10	10	10
Pumped storage	2.6	3	3	3	3	3	3	3
TOTAL	346.3	344	353	362	382	382	382	382
MtCO2/yr	153.7	147.1	138.9	134.0	126.9	88.1	71.3	72.2
Mean kgCO2/kWh including 8% transmission losses	0.479	0.462	0.425	0.400	0.359	0.249	0.201	0.204
Mt CO2 to storage						0	54	31
Low emission power	30%	32%	32%	31%	26%	30%	52%	57%
% gas	37%	34%	37%	44%	59%	69%	50%	64%

Potential UK CO_2 storage capacity

The UK has significant CO_2 storage opportunities offshore, with CO_2 sources relatively close to potential storage sites. Storage capacity for UK oilfields as a result of enhanced oil recovery has been estimated at approximately 700 $MtCO_2$. CO_2 storage capacity for many of the UK gas fields has been estimated on the basis that 90% of the pore space occupied by the recoverable reserves of depletion drive fields and 65% of the pore space occupied by the recoverable reserves of water drive fields could become available for CO_2 storage. On this basis, storage capacities in the Southern North Sea Basin are approximately 3.7 gigatons (Gt) CO_2, the East Irish Sea Basin approximately 1 $GtCO_2$, and the Northern and Central North Sea Basin 0.8 $GtCO_2$ respectively.

Total CO_2 storage capacity of the UK oil and gas fields alone should therefore be in excess of 6 $GtCO_2$.

Storage capacity in saline aquifers has been estimated to be up to 14.25 $GtCO_2$ in the Southern North Sea Basin [7] and up to 0.63 $GtCO_2$ in the East Irish Sea Basin [8]. No detailed estimates have yet been made of the aquifer storage capacity of the Northern and Central North Sea Basin or the other sedimentary basins surrounding the UK. Thus the total CO_2 storage capacity of the UK continental shelf is likely to comfortably exceed 20 $GtCO_2$, although this is subject to considerable uncertainty until better characterisation data is available.

Social and economic factors

A range of stakeholders needs to participate in developing effective CCS strategies. The DTI Carbon Abatement Strategy (CAT) and the Research Councils' programme Towards a Sustainable Energy Economy (TSEC) are both planned to address CCS issues in depth, to place them in an integrated UK energy system context and to consider the social, environmental, economic, technological and other aspects. Environmental and health and safety issues surrounding CCS on a range of temporal and spatial scales will also need to be examined. In the longer term, it is hoped that a UK Carbon Dioxide Capture and Storage Authority will be established by the UK government to take overall responsibility for the regulation of this new industry and eventually to provide long-term stewardship for the CO_2 stored underground.

Approximate electricity generation costs with CCS

Electricity generation costs for the UK market have been estimated using the assumptions below. All cost data is, however, intrinsically variable and it is important to note that, with a proper uncertainty analysis, there would be some differences in the conclusions from the simple deterministic approach presented here.

- Discount rate of 10% and investment lifetime of 25 years
- 8000 hours operation per year
- Coal prices of £1.4/GJ (net) and gas prices of £4/GJ (net) (and £3/GJ and £5/GJ)
- CO_2 delivery pressure of 110 bar (and pipeline quality)
- Transport to offshore aquifer storage, total cost £5.50 per tonne CO_2 stored

Capital costs estimates used in the electricity cost calculations are taken as the total expenditure (i.e. including interest during construction, commissioning fuel etc., less any income from generation during trials) that would have been made for a new plant up to the end of its commissioning period. From this point on it can be assumed that the plant will be capable of achieving the design availability for the remainder of its investment lifetime. The plants here are assumed to be based on technology that is well-developed at the time they are built, so that build times are not extended while novel equipment is commissioned. Typical build times are assumed to be approximately 3 years for pulverised coal (PC) plants and 2.5 years for natural gas combined cycle (NGCC) plants.

In practice, capital costs can be expected to vary significantly between sites and over time. It is very likely that many new power plants in the UK will use existing sites; the extent to which the infrastructure in place will help to reduce overall plant capital costs will vary significantly. Factors such as currency exchange rates, whether manufacturers' order books are full or empty, metal prices etc. will also affect actual costs significantly for all types of power plant.

In addition, there is obviously no market experience for new coal plant in the UK, and relatively little in Europe as a whole (and much of that is for German brown coals (lignites), so not directly relevant). So while a single 'reasonable' estimate has been made for capital plant costs for pulverised coal plant in the UK, a typical variability of at least +/-20% is estimated for the quoted capital costs, leading to roughly +/- 10% variability in costs of generation for coal plants. This is a real variability, which generators will perceive and have to include in their own pre-feasibility study cost assessments.

Supercritical pulverised coal plant equipment costs for a 750MW plant are given as 1222 $/kW in a recent IEA study [4], and this is also a reasonable typical value from the literature. Based on build times and expenditures it is estimated that this would be increased by approximately 15% to give the initial plant capital costs that have to be recovered over the life of a plant. With an estimated exchange rate (for the date of the IEA study) of $1.6/£ this gives a value of 880 £/kW.

Integrated gasifier combined cycle (IGCC) capital costs without capture are even more uncertain than for PC plant, since there is very limited experience. It has been assumed, based on current US market expectations, that IGCC specific capital costs without capture would be 10% higher than for PC without capture (with no benefit in efficiency, so costs for IGCC without capture have not been presented). Based on recent IEA GHG studies [5], it has been estimated that IGCC plant with capture would require an increase of 30% in the specific capital costs compared to IGCC without capture, for a low-cost/low-efficiency wet-quench gasifier system suited to CO_2 capture.

NGCC (natural gas combined cycle) costs were estimated from costs in [4] of 499 $/kW equipment costs for a 776 MW plant. With an estimated increase of 10% to the end of the commissioning period (vs 15% for PC, reflecting the shorter construction period for NGCC) and an exchange rate of $1.6/£ this gives a rounded initial project capital value of £340/kW. For post combustion capture, the specific capital cost is estimated to increase by 75%, in line with estimates from the same IEA GHG study. No values have been supplied for pre-combustion capture with NGCC, since whether or not this technology option is competitive with post combustion capture is expected to depend on local site-specific factors (e.g. space availability) [6].

To assess the value of achieving capital cost reductions through effective use of existing infrastructure and technical developments, some cost results are also presented for 20% lower capital cost estimates. Cost estimates 20% higher than central values are also used, indicating possible cost levels for early plants which have higher financing costs as well as much less benefit from experience.

A wide range of O&M costs are reported in the literature, possibly reflecting the scope of the costs that are included (e.g. taxes) and the different manning levels in publicly owned and private utilities. IEA GHG study values appear high compared to a survey of other studies [7,8,9]. Tentatively, estimated annual O&M costs of £30/kW have been used for supercritical PC plant, £35/kW for IGCC plant, £15/kW for NGCC and £30/kW for NGCC plant with capture.

An efficiency without capture of 44% LHV is assumed for advanced supercritical steam plant (600/620ºC single reheat). A capture penalty of 6.5 percentage points from an initial efficiency of 40% is assumed for IGCC. A non-capture efficiency of 56% and a capture penalty of 6 percentage points is assumed for the NGCC plant (based on two GE 9FA turbines with a single steam turbine). For the NGCC capture case it is assumed that post combustion capture is being used. Pre-combustion capture with natural gas does not appear to give a better performance [6] although it might be used under certain circumstances (e.g. limited space).

Electricity generation costs estimated on the basis described are presented in Table 2. It must be recognised, however, that, while it is useful to have discrete values, the tables and trend diagrams presented are still only generalised and approximate costs (as are nearly all of the generation cost estimates presented in the UK energy debate) and should not be over-interpreted. There is no substitute for site-specific and time-specific project costs, and these will vary from each other and from the estimates presented. It is also worth noting that no mechanism exists in the current UK market explicitly to relate electricity price to total generation costs. Electricity wholesale prices are generally set by marginal operating costs.

Table 2 Electricity cost estimates under a range of assumptions for UK power plants, with and without CCS

Plant name (net electrical output approx. 800MW)		**Supercrit Pulverised Coal**	**IGCC + precom**	**NGCC £4/GJ**	**NGCC £3/GJ**	**NGCC £5/GJ**	**NGCC £4/GJ + postcom**	**NGCC £3/GJ + postcom**	**NGCC £5/GJ + postcom**
Total plant cost at end of commissioning	£/kW	880	1258	340	340	340	595	595	595
Efficiency (LHV)	% LHV	44.0%	33.5%	56.0%	56.0%	56.0%	50.0%	50.0%	50.0%
% CO2 captured		0%	85%	0%	0%	0%	85%	85%	85%
Fuel cost (LHV)	**£/GJ**	**1.4**	**1.4**	**4**	**3**	**5**	**4**	**3**	**5**
	p/kWh heat	0.50	0.50	1.44	1.08	1.80	1.44	1.08	1.80
CO2 emissions on LHV heat basis	gCO2/kWh heat	325	325	210	210	210	210	210	210
CO2 emissions	gCO2/kWh elec.	739	146	375	375	375	63	63	63
CO2 captured	gCO2/kWh elec.	0	825	0	0	0	357	357	357
Operating hours	hrs/yr	8000	8000	8000	8000	8000	8000	8000	8000
Load factor		91.3%	91.3%	91.3%	91.3%	91.3%	91.3%	91.3%	91.3%
Discount rate	%	10%	10%	10%	10%	10%	10%	10%	10%
Plant life	years	25	25	25	25	25	25	25	25
Capital recovery factor	%/yr	11.02%	11.02%	11.02%	11.02%	11.02%	11.02%	11.02%	11.02%
Annual capital charges	£/kW/yr	96.95	138.64	37.46	37.46	37.46	65.55	65.55	65.55
Operation & maintenance	£/kW/yr	30	35	15	15	15	30	30	30
CO2 storage cost (part of 10MtCO2/yr aquifer/gas field storage system)	£/tonne CO2	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
EU ETS CO2 Emission Allowance cost	£/tonne CO2	15	15	15	15	15	15	15	15
Cost of electricity									
Capital	p/kWh	1.21	1.73	0.47	0.47	0.47	0.82	0.82	0.82
Operating expenditure	p/kWh	0.38	0.44	0.19	0.19	0.19	0.38	0.38	0.38
Fuel	p/kWh	1.15	1.50	2.57	1.93	3.21	2.88	2.16	3.60
CO2 storage costs	p/kWh	0.00	0.45	0.00	0.00	0.00	0.20	0.20	0.20
Cost of electricity ex. EU ETS	**p/kWh**	**2.73**	**4.13**	**3.23**	**2.58**	**3.87**	**4.27**	**3.55**	**4.99**
Low capital (-20%)	p/kWh	2.49	3.78	3.13	2.49	3.78	4.11	3.39	4.83
High capital (+20%)	p/kWh	2.97	4.48	3.32	2.68	3.96	4.43	3.71	5.15
Emission allowance costs	p/kWh	1.11	0.22	0.56	0.56	0.56	0.09	0.09	0.09
Cost of electricity inc. EU ETS	**p/kWh**	**3.84**	**4.35**	**3.79**	**3.15**	**4.43**	**4.37**	**3.65**	**5.09**
Low capital (-20%)	p/kWh	3.60	4.00	3.70	3.05	4.34	4.20	3.48	4.92
High capital (+20%)	p/kWh	4.08	4.69	3.88	3.24	4.53	4.53	3.81	5.25
Break-even carbon price for CCS rel. to central PC cost	**£/tonne CO2**	**0.00**	**23.54**	**13.61**	**-4.07**	**31.29**	**22.77**	**12.11**	**33.43**
Low capital (-20%)	£/tonne CO2		17.70						
High capital (+20%)	£/tonne CO2		29.38						
Marginal cost of generation (i.e. minimum electricity price at which plant will be operated once built)									
Fuel	p/kWh	1.15	1.50	2.57	1.93	3.21	2.88	2.16	3.60
CO2 storage costs	p/kWh	0.00	0.45	0.00	0.00	0.00	0.20	0.20	0.20
Emission allowance costs	p/kWh	1.11	0.22	0.56	0.56	0.56	0.09	0.09	0.09
Marginal cost of generation	**p/kWh**	**2.25**	**2.18**	**3.13**	**2.49**	**3.78**	**3.17**	**2.45**	**3.89**

Technology options for minimum cost of electricity with assumed constant coal price and varying gas and carbon (CO_2) prices are shown in Figure 1. Since gas and carbon prices tend to be correlated, it may be that lowest cost plant goes directly from being unabated gas to coal with capture as carbon constraints increase.

Conclusions

A multidisciplinary project has been initiated to examine a wide range of issues related to CCS deployment in the UK. Preliminary results suggest that, if required, CCS could be used to achieve significant emission reductions in the UK electricity sector by 2020. Offshore CO_2 storage capacity is available to support this.

Preliminary and approximate electricity cost estimates suggest that carbon prices in the range of £20-30/tonne CO_2 might be needed to make CCS viable in the UK. Unabated natural gas power plant is still likely to be the cheapest generation option in the current market, but coal plants with CCS would be preferred at higher gas and carbon prices and, once built, would have relatively low marginal generation costs.

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References

[1] UEP, (2004) *Updated UK Energy Projections*, DTI Working Paper, May 2004.

[2] Gibbins, J., Haszeldine, S., Holloway, S., Pearce, J., Oakey, J., Shackley, S., and Turley, C., *Scope for Future CO_2 Emission Reductions from Electricity Generation through the Deployment of Carbon Capture and Storage Technologies*, Defra Conference "Avoiding Dangerous Climate Change", Exeter, Feb 1-3, 2005.

[3] BP, *BP and Partners Plan Clean Energy Plant in Scotland, Increasing Oil Recovery And Reducing Emissions*, BP Press Release, 30 June 2005. (http://www.bp.com/genericarticle.do?categoryId=2012968&contentId=7006999)

[4] IEA GHG PH4/33, *Improvements in Power Generation with Post Combustion Capture of CO_2*, Nov 2004.

[5] IEA GHG PH4/19, *Potential for Improvement in Gasification Combined Cycle Power Generation with CO_2 Capture*, May 2003.

[6] IEA GHG 2005/1, *Retrofit of CO_2 Capture to Natural Gas Combined Cycle Power Plants*, Jan 2005.

[7] Royal Academy of Engineering, *The Costs of Generating Electricity*, March 2004. (http://www.raeng.org.uk/policy/reports/electricityreports.htm)

[8] S. Dalton, *Cost Comparison IGCC and Advanced Coal,* EPRI Roundtable on Deploying Advanced Clean Coal Plants, July 29, 2004 (http://www.climatevision.gov/pdfs/coal_roundtable/dalton.pdf)

[9] IEA, *Projected costs of generating electricity, 2005 update.* (http://www.iea.org/w/bookshop/add.aspx?id=196)

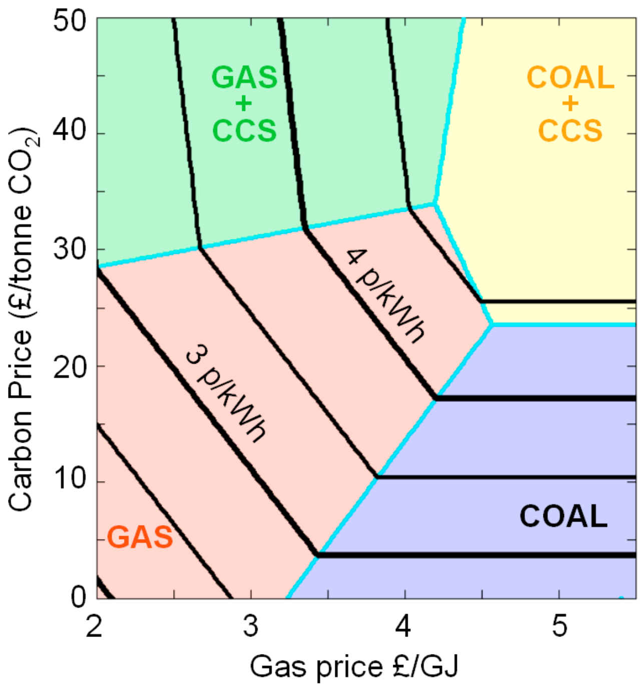

Figure 1 Estimates for lowest cost generation option as a function of gas and carbon prices
(Coal price: £1.4/GJ, 25 year plant life, 10% IRR)