Product title/description: Assessment of the validity of “Approximate minimum land footprint for some types of CO_2 capture plant” provided as a guide to the Environment Agency assessment of Carbon Capture Readiness in DECC's CCR Guide for Applications under Section 36 of the Electricity Act 1989

Product authors: **Nick Florin (n.florin@imperial.ac.uk), Paul Fennell (p.fennell@imperial.ac.uk)**

The authors are very grateful for generally helpful comments received from: Blyth Park Power, Carlton Power, Edinburgh University, Mott MacDonald, RWE NPower, SKM, USR Corporation and also Parsons Brinkerhoff.

Executive Summary

Under Section 36 of the Electricity Act 1989, applicants are required to demonstrate that there is sufficient space available on site, or near enough to the generation equipment, such that they will be able to retrofit carbon capture equipment in the future. To this end, minimum approximate land footprint requirements are outlined in the Guidance Note based on data from an IEA report (2006/8) published about five years prior to the present day. This is a significant period of time in terms of the development of CO_2 capture technologies and generation systems; and thus, the data given in the Guidance Note, with particular to reference to the retrofit of CCS to CCGTs, does not reflect the land footprint requirements for today's technology. The remit of this report is to assess the up-to-date, publicly available, literature; a detailed engineering design study is outside the scope of this work.

The validity of the land footprint requirements were assessed by reviewing data published by the United States Department of Energy/ National Energy Technology Laboratory (DOE/NETL,2007a,b), the Global Carbon Capture and Storage Institute (GCCSI, 2010) and Department of Energy and Climate Change (DECC, 2009b). For the retrofit of CCS to coal-fired power stations, these reports present consistently larger land footprints compared to those from the IEA report (2006/8); however, any reasonable comparison is difficult due to the different assumptions made in terms of equipment list and the different basis chosen for these studies in terms of plant capacity. Regarding the retrofit of CCS to CCGT plants, there is very limited information available.

In the contentious case of post-combustion retrofit of CCGT plants, it appears that the original space requirements estimated in the IEA report (2005/1)) for a 785 MWe power station (pre-retrofit) have been directly transcribed into the Guidance which assumes a 500 MWe power station (later clarified by Mott MacDonald to be with CO_2 capture, i.e., post-retrofit), without adjustment for the different basis. It is also relevant to note that the original study (IEA, 2005) assumed two GTs with eight trains of CO_2 capture equipment, which was conservative with respect to column sizing and may now be outdated. Notwithstanding the clarification offered by Mott MacDonald, the Guidance is ambiguous regarding whether the assumed net capacity is based on capacity, with or without CO_2 capture, and the authors suggest that the data given in the Guidance are generally taken as the **net capacity before retrofit of capture plant—thus the corrections recommended herein are made on this basis**.

Accordingly, we make the following recommendations:

- No reduction in the approximate land footprint for coal-fired power stations is recommended
- The data included in the Guidance Note for post-combustion retrofit of CCGTs should be reduced by at least 36 % assuming the same list of equipment for a gas plant with an output of 500 MWe without capture (see Table A1, p. 29). This reduction is not applicable under different assumptions, e.g., Mott MacDonald suggests a 20 % reduction including space for new stacks or additional cooling capacity with an assumed net capacity of 500 MWe after retrofit of capture plant.
- In general, using a linear scaling factor is overly simplistic – it would be more reasonable to take a modular approach and scale foot print with respect to the number of turbines and capture trains.
- A correction to the reduced basis of 500 MWe may also be appropriate for estimates of the space requirements for the retrofit of pre-combustion capture equipment to CCGT and for IGCC plants; however, this review has not focused on these technologies in light of the majority of recent applications submitted to DECC, and given the very limited availability of information.
- There appears further scope to reduce the land foot print estimate for a CCGT with post-combustion capture by up to a total reduction of about 50 % (i.e., including the 36 % reduction) considering technology advances and with layout optimisation (e.g.

assuming one capture train per GT, or three-to-two); however, such a reduction can only be justified on the basis of a detailed engineering design (which is not a requirement for consent under Section 36).

- Due to the paucity of data for CCGTs, a detailed study for a generic CCGT retrofit should be conducted with specific focus on land footprint requirements
- To avoid ambiguity and facilitate comparison, minimum land footprint estimates must specify all of the assumed equipment, including: generation system (incl. use of auxiliary supply, steam supply), CO_2 capture equipment (incl. column sizing for absorber and stripper, number of trains), cooling systems, CO_2 dehydration and compression (incl. number of compressors per train), additional flue gas treatment (incl. scope to incorporate within existing facilities), solvent/sorbent storage, CO_2 transport details (incl. pipelines), space for construction, appropriate space for health and safety
- Minimum land footprint estimates must clearly state assumptions regarding power output, including whether the footprint estimates incorporates additional plant modifications to maintain power output post-retrofit

Contents

Appendices

Summary of terms

AEP American Electric Power

ASC BTR advanced supercritical boiler turbine retrofit

CCR carbon capture ready

CCS carbon capture and storage

CCCP combined cycle cogeneration plant

CO_2 carbon dioxide

DECC Department of Energy and Climate Change

DOE Department of Energy (USA)

FGD flue gas desulphurisation

GCCSI Global Carbon Capture and Storage Institute

GHG greenhouse gas

GT gas turbine

H_2S hydrogen sulphide

HAZOP hazard and operability

IEA International Energy Agency

IGCC integrated gasification combined cycle

MEA monoethanolamine

MWe mega-watt electricity

NETL National Energy Technology Laboratory (USA)

NG natural gas

NGCC natural gas combined cycle

PC pulverised coal

SC supercritical

SCPC supercritical pulverised coal

SCR selective catalytic reduction

USCPF ultrasupercritical pulverised fuel

§1.0 Introduction

For consent under Section 36 of the Electricity Act 1989, applicants are required to demonstrate that *"sufficient space is available on or near the site to accommodate carbon capture equipment in the future".* The proposed equipment must be sized such that the capability exists for *"processing emissions from the entire power station".*

Accordingly, indicative land footprint requirements are outlined in the Guidance Note for Section 36 based on the IEA report (2006/8): *CO_2 capture as a factor in power plant investment decisions*. The data, i reproduced in Table 1, provides an "approximate minimum land footprint" for gas and pulverised coal plants with net capacity of about 500 MWe (without capture, i.e., pre-retrofit) using different CO_2 capture technologies. The authors' acknowledge that some ambiguity remains regarding whether the assumed net capacity is based on plant capacity, with or without CO_2 capture, however suggest that the data given in the Guidance is generally taken as the net capacity before retrofit of CO_2 capture plant.

Table 1. Reproduction of '*Table 1. Approximate minimum land footprint for some types of CO_2 capture plant'* from Carbon Capture Readiness: A guidance note for Section 36 Electricity Act 1989 consent applications (DECC 2009a)*.

<table>
<tr><th></th><th>CCGT with post-combustion capture</th><th>CCGT with pre-combustion capture</th><th>CCGT with oxy-combustion capture</th><th>USCPF with post-combustion capture</th><th>IGCC with capture</th><th>USCPF with oxy-combustion capture</th></tr>
<tr><td>Approx. net capacity without capture (MWe)</td><td>785</td><td>785</td><td>500</td><td>500</td><td>785</td><td>500</td></tr>
<tr><td>Site dimensions for generation equipment (m)</td><td>170×140</td><td>170×140</td><td>170×140</td><td>400×400</td><td rowspan="2">475×375</td><td>400×400</td></tr>
<tr><td>Site dimensions for CO_2 capture and compression equipment (m)</td><td>250×150**</td><td>175×150**</td><td>80×120</td><td>127×75</td><td>80×120</td></tr>
<tr><td>Total site footprint (m^2)</td><td>62 000</td><td>50 000</td><td>34 000</td><td>170 000</td><td>180 000</td><td>170 000</td></tr>
</table>

*****This table was reproduced from the IEA GHG report (2006/8) CO_2 capture as a factor in power plant investment decisions (Table 3-10)

****** This data was sourced from IEA Report (2005/1) Retrofit of CO_2 Capture to Natural Gas Combined Cycle Power Plants which assumed a net capacity without capture of 785 MWe

Details relevant to demonstrating that the proposed space is suitable, as refrred to in the Guidance Note(DECC, 2009a), include: (i) the footprint of the combustion plant, (ii) the location of the capture plant including any air separation units, (iii) the location of the CO_2 compression equipment, (iv) the location of any chemical storage facility, and (v) the exit point for CO_2 pipelines from the site. It is apparent that a more detailed equipment list is necessary to eliminate ambiguity and facilitate a meaningful comparison, including: (i) generation system (incl. use of auxiliary supply, steam supply), (ii) CO_2 capture equipment (incl. column sizing for absorber and stripper, number of trains), (iii) cooling systems, CO_2 dehydration and compression (incl. number of compressors per train), (iv) additional flue gas treatment (incl. scope to incorporate within existing facilities), (v) solvent/sorbent storage, (vi) CO_2 transport details (incl. pipelines), and (vii) space for construction

In addition, consideration of the percentage of CO_2 to be captured, with reference to an approximate net capacity, must be presented including calculations determining the likely volumes of CO_2 to be captured. This is relevant because plants which have the capability to capture a large percentage of their CO_2 emissions will require larger equipment; capture of 90 % is a reasonable target given uncertainties in terms of future abatement requirements.

Further assumptions relevant to the estimate of the approximate minimum land footprint are the potential need for the installation and/or modification of equipment for flue gas desulphurisation (FGD), and deNO_x treatment (selective catalytic reduction, SCR). There is a range of perspectives in the literature regarding the need for additional polishing FGD and NO_x treatment (see Comments Received). There is an economic trade-off between investing in addition plant equipment (e.g.: SCR) vs. the cost of solvent consumption—it is important that all assumptions related to additional flue gas treatment be included in the land footprint estimates.

The data presented in Table 1 was published about five years ago, which is a significant period of time in terms of the development of CO_2 capture technologies and generation systems; thus, the data given in the Guidance Note does not reflect the land footprint requirements for today's technology. On this basis, and given a number of recent applications submitted to DECC(i.e.: 11 applications for CCGT power plants and 1 for a coal-fired power plant), that do not comply with the approximate minimum land footprint requirements, this report provides an up-to-date review of the literature relevant to assessing whether the data is valid in 2010.

We first discuss the source of the original data (Table 1) and the relevant assumptions (§2.0). In §3.0 we compare those data with more recent studies published by The United States Department of Energy/ National Energy Technology Laboratory, DOE/NETL (2007a,b), The Global Carbon Capture and Storage Institute, GCCSI (2010) and a recent report prepared by Doosan Babcock Energy Limited for DECC (2009b).These references are for studies that have focused on the retrofit of CCS to coal-fired power plants and this is because there is a paucity of literature that consider CCGTs highlighting the need for a detailed engineering design study for a generic CCGT with CCS

§2.0 Source of original data and key assumptions

Data presented in the IEA 2006/8 report assumes plant capacities of about 500 MWe (clarified by Mott MacDonald to be with capture, i.e., post-retrofit); however, the source of the data for CCGT with post-combustion capture, CCGT with pre-combustion capture, and IGCC with capture originates from an earlier IEA document (2005/1)[1] which assumed a basis of 785 MWe (without capture) and 626 MWe (post-retrofit)[2]. Notwithstanding the clarification offered by MM, there remains ambiguity regarding whether the assumed net capacity is based on capacity with or without CO_2 capture and the authors assert that the data given in the Guidance are generally taken as the net capacity before retrofit of capture plant—thus the corrections given are made on this basis. The numbers were **directly transcribed** into the IEA (2006) report with **no adjustment for the decrease in the net capacity** (before CO_2 capture) by 36 % for the same assumed equipment. Although the approximate minimum land requirement may not be directly proportional to the net capacity of the power plant, **the footprint would be significantly reduced because the amount of CO_2 to be processed would be significantly less**. We do not advocate the use of a linear scaling factor to relate power output to approximate land footprint, however in this instance we argue that a linear reduction of at least 36 % is appropriate for a CCGT with post-combustion capture (see Table A1, p. 29). This reduction may not be applicable under different assumptions, e.g., Mott MacDonald suggests a 20 % reduction including space for new stacks, or additional cooling capacity, with an assumed net capacity of 500 MWe after retrofit of capture plant. In general, using a linear scaling factor is overly simplistic – it would be more reasonable to take a modular approach and scale footprint with respect to the number of turbines and capture trains. We note a correction to a basis of 500 MWe pre-retrofit may also be appropriate for estimates of the space requirements for the retrofit of pre-combustion capture equipment to CCGT and for IGCC plants; however, this review has not focused on these technologies in light of the majority of recent applications submitted to DECC. Given the very limited availability of information there is considerable scope for further work.

There is general consensus in the field (see Comments Received) that the original Jacob's study (IEA, 2005) was very conservative with respect to column diameter leading to an assumed eight capture trains for two GTs. Hence, there appears to be scope to further reduce this footprint by up to about 50 % (= 18 750 m^2 for 500 MWe before retrofit) owing to advances in generation and CO_2 capture technology, and with layout optimisation. For example, the Fluor/Statoil (2005) 'non-confidential' feasibility study reports 15 m as a maximum diameter for absorption columns and on this basis assign three absorption trains for two GTs (about 250–300 MWe); more recently the SKM (2009) report assumes one capture train per 500 MWe GT. That said, such a reduction can only be reasonably assessed on the basis of a detailed engineering design (which is not currently required for consent under Section 36).

[1] The IEA (2005/1) study was based on a 785 MWe (without capture) natural gas fired combined cycle plant (including 2 GE 9FA gas turbines). The work considers five options for retrofit, including: post-combustion capture of CO_2 with eight CO_2 capture trains (using MEA); pre-combustion (Selexol) reforming of NG with CO_2 capture on site; pre-combustion reforming of NG with CO_2 capture on a remote site (40 km from plant); gasification of coal (GE slurry feed) with pre-combustion CO_2 capture on site; and gasification of coal with pre-combustion CO_2 capture on a remote site. The size requirement is at the top of page 92.

[2] The relative areas for plants with and without CO_2 capture do not take into account the reduction in power output when capture is added. Therefore a larger footprint would be required to achieve the same power output with capture to accommodate the increase in fuel consumption and a subsequent increase in the amount of flue gas to be processed.

The approximate land footprint for post-combustion capture from a gas plant is considerably larger compared to a coal plant; furthermore, because the footprint for generation is smaller for gas than coal, the land footprint for capture represents a much larger fraction of the total land footprint. For example, based on data in Table 1, for CCGT with post-combustion capture, an increase of 110 % in the land footprint is required for capture compared to only 6 % for capture from USCPF plant—however, noting that the total land requirements are estimated at 62 000 and 170 000, respectively. (These comparisons are based on original data given in the Guidance.)

A constraint for size reduction via layout optimisation specific to post-combustion retrofit to CCGT is the need to place the capture plant next to the CCCP (combined cycle cogeneration plant) due to the huge volumes of atmospheric flue gas with very low concentration of CO_2 between about 3–5 vol % (IEA, 2005)[3]. Thus, transport of the flue gas over even short distances may not practicable due to pressure loss and cost of large diameter piping. On this basis, the scope for layout optimisation resulting in a reduced footprint for capture may be limited. A further constraint relevant to the space requirements for the retrofit of capture equipment to gas plants is the management of the NO_x levels. There is a range of perspectives in the literature regarding the need for NO_x treatment. For example the IEA report (2006) suggests it is likely that gas power plants would require equipment for NO_x removal during CO_2 capture retrofitting to avoid the costly degradation of the solvents. However, there appears possible scope for such equipment to be incorporated into existing facilities, e.g.: NO_x treatment may be installed in the HRSG (see Appendices).

[3] The concentration of CO_2 in the flue gas from coal plant is about 12 vol %

§3.0 Up-to-date review of literature

Subsequent to the IEA (2006) report, we have reviewed four published studies which present new estimates for the approximate minimum land footprint for different CO_2 capture technologies. These include two reports published by the US DOE/NETL (2007a, b), a report commissioned by the GCCSI (2010), and a recent study prepared by Doosan Babcock Energy Limited for DECC (2009b). These are discussed in turn.

The **DOE/NETL (2007a)** conducted a study that evaluated the technical and economic feasibility of retrofitting different levels of capture (from 30–90 %) on an existing pulverised coal-fired power plant – American Electric Power's (AEP) Conesville No. 5 unit, Ohio – using "an advanced state-of-the-art amine-based" (ca. 2006) post-combustion CO_2 capture[4].The net plant power output without CO_2 capture was 433.8 MWe. Signifiicant reductions in the power output were calculated as a result of the capture system in the range of 10–30 %; i.e., the net reduction in plant output for 90 % CO_2 capture was about 130 MWe (30 %) compared to 43 MWe (10 %) with 30 % CO_2 capture. The study made no adjustment for the reduction in the net power output with capture. The coal feed rate was unchanged from the base case, however natural gas was used to supplement steam extraction to regenerate the solvent.

The authors of this study conclude that about 4 acres (1 acre = 4046.856 m^2) or 16 187 m^2 for amine based CO_2 capture equipment and compression equipment for 90 % CO_2 capture from a 433.8 MWe unit. This estimate is in close agreement with GCCSI study (Table 2) and significantly greater than the estimated 9 525 m^2 for a 500 MWe unit from the IEA (2006) study (Table 1). The specific breakdown was one acre for the absorber, one acre for the stripper and two acres to accommodate the compression and liquefaction system. The estimated space requirement is assumed to be 'slightly smaller' corresponding a reduction in the amount of CO_2 captured (i.e., by bypassing some of the flue gas the capture equipment can be scaled down). It is worth noting that these space requirements are estimated for an existing plant rather than a new CCR design. There is significant potential for utilisation of heat rejected from the CO_2 capture and compression system can be integrated with the steam/water cycle if they are located in close proximity highlighting the importance of space being available in critical locations.

A second **DOE/NETL report (2007b**), that reviews environmental impacts associated with CO_2 sequestration, briefly considers the space requirements for CO_2 compression. Specifically, the report discusses the equipment and space requirements for compression prior to transport of CO_2 to appropriate storage locations by assuming two generalised model scenarios, including: a gas stream with and without H_2S (i.e., relevant to CO_2 processing from an IGCC plant); and different scales, from pilot- (200 MT CO_2 per day) to commercial-scale (2740 MT CO_2 per day).

The space requirements for the pilot-scale facility – which does not include capture equipment – consisting of four compressors and one pump (with electric motors powered by the combustion of some additional NG) was estimated to require 2 acres of land (about 8 094 m^2). The commercial-scale facility consisting of 8–10 compressors and two pumps was estimated to require 20 acres of land (about 80 937 m^2). These estimates, despite the very different assumptions regarding the model systems, including no consideration of land requirements for the capture equipment, are significantly greater than those estimated in the earlier DOE/NETL (2007a) study, i.e.: by a factor of ten for compression only.

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[4] AEP's Conesville No. 5 is one of six plants located on a 200 acre site in Conesville Ohio with a combined generating capacity of about 2080 MWe. No. 5 is a sub-critical pulverised-coal-fired steam generator with a capacity of about 450 MW. The plant uses bituminous coal from Ohio; Particulate matter is removed an ESP and SO2 is removed with a lime-based FGD

We note that there is scope to reduce the space requirements for compression with the use of today's technology, e.g., URS (see Comments Received) argue that two centrifugal compressors per train is likely to be sufficient for a reliable system.

The **GCCSI (2010)** has recently commissioned a report which proposes an 'internationally recognised definition of Carbon Capture and Storage Ready'. This report presents space requirements for a 600 MW super critical pulverised coal plant (SCPC) with amine-based post-combustion capture and this is compared with an oxy-fuel-based system (Table 2). The data for the post-combustion option was based on modelling using commercial packages, e.g., Thermoflex and ASPEN PLUS[5] and the data for the oxy-fuel capture system was reproduced from DECC (2009), discussed below. The estimated land footprints presented in this report (including the DECC data) are significantly higher compared to those presented in Table 1. Although no specific data was included for NGCC with post-combustion capture, the GICCS report states that the land requirements for an amine-based post-combustion plant retrofitted to a NGCC would be larger than that of a similar capture plant for a coal plant, with the same generating capacity. This is due to the lower concentration of CO_2 and the higher volumetric flowrate of the flue gas—thus, requiring larger and/or additional absorption columns. However, the total amount of CO_2 is smaller for the gas plant, hence less space may be needed for all other components cancelling out some of the additional space requirements. This point of view is a major point of contention and is discussed in detail in the Comments Received.

The estimate presented for SCPC with amine-based capture is higher than the numbers presented in the DECC report (2009b) presumably because the former accounts for the footprint of the FGD and space requirements to accommodate $DeNo_x$ equipment. By contrast, the DECC (2009) study only considers modifications, i.e., including sufficient space to accommodate a polishing unit (including associated duct work) for SO_2 reduction, and a $DeNo_x$ plant (SCR) was assumed unnecessary in this case.

Table 2. Reproduction of *Exhibit 2-2: Space Requirements for CO2 Capture Plant for a 600 MW Supercritical PC Plant and Oxy-fuel CO2 Capture System,* (GCCSI, 2010)

	Supercritical PC plant with amine-based post-combustion CO_2 capture	Oxy-fuel CO_2 capture system
CO_2 capture and compression plant (m^2)	15 625	23 600*****
FGD plant/SCR (m^2)	15 000	-
Water treatment, waste water tank, limestone storage, gypsum dewatering, gypsum silo, stacking tank (m^2)	7 500	-

***** According to footnote *Number 28* in the GCCSI(2010) report the data for oxy-fuel CO_2 capture was taken from DECC (2009b); the estimate includes the associated land footprint for two air separation units (11 200 m^2) and compression (1200 m^2)

The **DECC (2009)** report which was prepared by Doosan Babcock Energy Limited (and collaborators, including: Alstom, E.ON UK, Air Products plc, Imperial College London and Fluor Ltd) assessed the technical and economic feasibility of retrofitting CO_2 capture technology to supercritical PC power plants in the UK. The Ratcliffe Power Station, which consists of four 500 MWe boiler/turbine units, was selected as the reference site for the study. The approximate footprint estimates were made based on only one of the four boiler/turbine units, and it was assumed that the retrofitted boiler/turbine unit be located in

[5] Modeling was carried out by Aurecon, Australia

the boiler and turbine house, replacing the existing subcritical unit. Three retrofit options were considered, including Advanced Supercritical Boiler/Turbine Retrofit (ASC BTR), ASC BTR with amine-based post-combustion CO_2 capture, and ASC BTR with oxy-fuel CO_2 capture system The report also discussed the applicability of the retrofit study to other UK coal-fired plant sites such as Drax and West Burton. The approximate footprints for the different retrofit options are reproduced in Table 3.

The authors (DECC 2009) note that the approximate footprint is estimated based on the size of equipment, as well as access requirements for installation and maintenance; the latter likely to be very site specific. In line with this it was asserted that there is significant scope for layout optimisation which could lead to footprint reduction by up to about 20 %. Obviously this would need to be assessed on a case-by-case basis.

Table 3. Reproduction of *Table 2.11-1 Approximate Footprint Requirements of CO_2 Capture Plant*, DECC (2009)

	Subcritical existing unit (Ratcliffe; one of four boiler/turbine units)	Advance Super Critical Boiler/Turbine retrofit (ASC BTR)	ASC BTR with amine-based CO_2 capture	ASC BTR with oxy-fuel CO_2 capture system
Approx. Unit net capacity (MWe)	500–660	615–660	540–600	630–660
Site dimensions for generation equipment (m^2)	140 000	140 000	140 000	140 000
Site dimensions for CO_2 capture equipment (m^2)	-	-	23 000	18 700
Site dimensions for CO_2 compression equipment (m^2)	-	-	825	5 800

Conclusions

The land footprints for capture plant retrofit to coal plant in the IEA report (2006), and subsequently used in the CCR Guidance Note, are less than those estimated in the more recent studies cited in this review. Data published by the GCCSI (2010) are in reasonable agreement with the DOE/NETL (2007a,b) and recent DECC (2009b) reports, recognising the different assumptions adopted (in terms of equipment list and plant capacity) in these studies which cause some variation.

Variation in the numbers is directly dependent on the assumptions made and highlights the importance of including a detailed equipment list. For example, GCCSI (2010) considers the footprint for FGD and SCR in the case of the SCPC plant with amine-based capture resulting in a higher estimate than that presented in the DECC (2009b) report which assumes modifications to the existing FGD plant. Furthermore, a number of the retrofit studies discussed are based on existing sites and assumptions about layout are very site specific. While there may be scope for space reductions due to layout optimisation – the allocation of space for equipment, access for installation/maintenance/delivery of equipment and consumables, as well as space allocation based on HAZOP studies for storage of chemicals – unavoidably limits the potential size reduction by layout optimisation, to about 20 % (DECC, 2009b).

Based on this review it is concluded that any substantial reduction in the approximate land footprint for coal-fired power stations based on the CCR Guidance Note for Section 36 is improbable.There is significantly less information available in the literature considering CCGT retrofit compared to the retrofit of coal-fired power stations, and this is an area requiring urgent further work.

In the case of post-combustion capture retrofit to CCGT plants, it appears that current Guidance uses the footprint for a 785 MWe (pre-retrofit) power station as the base case for a 500 MWe plant, without adjustment for the change in size of the plant output. Of course, the capture plant size will not scale directly with the size of the plant, but it is likely that the Guidance overestimates the size of capture plant required, by at least 36 %.

There appears further scope to reduce up to a total reduction of 50 % considering technology advances and via layout optimisation (e.g.. assuming one capture train for one GT); however, such a reduction can only be justified on the basis of a detailed engineering design which is not currently a requirement for consent under Section 36.

A correction to an assumed basis of 500 MWe pre-retrofit may also be appropriate for estimates of the space requirements for the retrofit of pre-combustion capture to CCGT and for IGCC plants; however, this review has not focused on these technologies in light of the majority of recent applications submitted to DECC. Given the very limited availability of information there is considerable scope for further work.

It is critical to note that location-specific issues (e.g., the quality and availability of cooling water) will cause significant differences in the size of CCS plant available. It is suggested that a modular/flowsheet approach to generating the recommended plant footprint should be adopted. This approach may be developed based on a detailed engineering design of a generic CCGT with capture plant and would eliminate ambiguity when scaling footprint estimates up for power plants with an output > 500 MWe pre-retrofit.

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Appendix A1 Comments Received on 1st Draft

Blythe Park Power John Wearmouth Snr, john@blytheparkpower.co.uk; http://blytheparkpower.co.uk/index.html	
(1) Since the publication of the CCR Guidance DECC have only received Section 36 applications for CCGT plants. There have been no applications for coal fired plant and, as any coal fired plant is now required to be fitted with 300 MW of CCS, the economic case for a coal fired plant does not exist and no applications can therefore be expected	Our remit was to critically assess the peer reviewed literature
(2) The literature reviewed is all related to coal fired plant and is therefore of limited value	The Jacobs review is for a gas turbine, although with a strong focus on the plant economics. The report notes the paucity of data for CCGT and recommends a detailed engineering design project based on a generic CCGT be conducted
(3) The Jacobs IEA 2005/1 report is for a 785 MWe plant. To apply it to a 500 MWe plant gives a reduction of 37%, not the 20% recommended for discussion by Imperial College.	We have sought clarification from Mott MacDonald and recommend up to 50 % reduction for a 500 MWe output (without capture) which includes adjustment of the assumed output and potential for layout optimisation with today's technology. We do not advocate a linear scaling factor is appropriate for relating power output to estimated land footprint for CCP. Instead, reference to specific equipment, including number of absorption columns, strippers, cooling systems, dehydration and compression systems, etc. would eliminate ambiguity and allow reasonable comparisons to be drawn.
(4) The 2005/1 report has eight trains of carbon capture equipment for the 785 MWe plant. The CCR report submitted to DECC alongside Section 36 applications are all for one train of	See previous response to comments

carbon capture equipment per unit (except for Damhead Creek II, which uses three trains for two CCGT units). We estimate that having one train per unit instead of four gives a further 50% reduction in the CCS plant footprint. Feasibility studies have been conducted for such single stream CCS plants. Table 1 of the CCR Guidance states site dimensions for 785MWe to be 250 m by 150 m = 3.75 ha. Correcting to 500 MWe gives 3.75 x 0.63 = 2.4 ha and for a single train of CCS per CCGT unit according to our 50% estimated reduction would give 2.4 x 0.5 = 1.2 ha.	
(5) This figure of 1.2 ha per 500MWe is close to that quoted in various CCR reports received by DECC, which have been accompanied by indicative equipment layouts.	The authors are aware that Blythe Park Power has submitted a proposal to build a 950 MW CCGT and is currently seeking the approval DECC
(6) There is no FGD or DeNOx equipment required for CCGT with CCS. Gas fired plants do not require SCR, and even if they did it could be accommodated in the HRSG (Heat recycle steam generator). It is quite common to leave space in the HRSG for SCR, even in current CCGT plants. It therefore has no affect on the area of the CCS plant.	There are a range of perspectives in the literature, e.g., Mott MacDonald (IEA, 2006/9) suggest that gas power plants are likely to require equipment for NO_x removal during CO_2 capture retrofitting to avoid the costly degradation of the solvents. We acknowledge that there will be an economic trade-off in terms of the cost of new equipment vs. input of fresh solvent.
(7) Comparing footprints of coal and CCGT plants is not relevant.	The draft report acknowledges the paucity of data for CCGTs and stresses the need for a detailed engineering design of a generic CCGT retrofit
(8) DOE/NETL (2007a) states 4 acres for 90% capture from 433.8MWe; 1 acre for the absorber/stripper and 2 acres for compressors. DOE/NETL (2007b) quotes 8-10 compressors and 2 pumps for 2740 tCO_2/d. We cannot understand why 8 compressors are needed for 2,740 tCO_2/d. Compression equipment exists such as the MAN RG140-8 which can compress up to 110 kg/sec of CO_2. One of these compressors is large	The authors agree and the report discusses the potential for technology improvements that may lead to footprint reductions and an increased scope for layout optimisation. The document has been revised

enough to handle all the CO_2 from a 500 MW unit whether it is CCGT, subcritical coal or supercritical coal (see table below).	accordingly.
(9) The GCCSI (2010) report erroneously states that the area for CCS for CCGT would be larger than for CCS for a coal fired plant due to the lower concentration of CO_2 in the CCGT flue gas. This ignores the fact that the amount of CO_2 captured from a coal fired plant would be 2 to 2.5 times as much as a similar sized CCGT plant. Hence, the quantities of MEA re-circulated, the lean MEA cooler, the MEA lean/rich heat exchanger, the stripper, the reboilers, the CO_2 condensers, the MEA storage and the CO_2 compressors are all larger than those required for a CCGT. We would expect that the space required for the CCS equipment for a 500 MWe coal fired plant would be significantly greater than that required for a CCGT plant, especially if extra FGD is required. GCCSI gives the following areas for a 600 MWe supercritical plant: CCS – 1.5 ha, FGD – 1.5 ha, Misc – 0.75 ha,TOTAL – 3.75 ha	We have updated the report to highlight this important point of contention. The issue would be easily resolved if all equipment required for CCP were identified and sized to facilitate an unambiguous comparison
(10) The table below shows dimensions and flow rates for a CCS plant on CCGT vs coal fired plants based on published calculations: As you can see, the amount of CO_2, solvent, steam and cooling water processed in a CCS plant on a coal fired unit is greater than on a CCGT. While the absorber would be smaller, all other items of equipment would be larger. The area required for a direct contact cooler for a CCGT is more than replaced by the FGD required for a coal fired plant.	See previous response to comments

Parameter	Units	CCGT	Subcritical Coal	Supercritical Coal
Unit size	MWe	500	500	500
Efficiency	%	58%	36%	46%
CV of fuel	MJ/kg	46	23.6	23.6
Fuel consumption	kg/s	18.7	58.9	46.1
Fuel carbon content	%	75%	60.3%	60.3%
CO_2 produced	kg/s	51.5	130.1	101.8

CO_2 removal	%	90%	90%	90%
CO_2 removed	kg/s	46.4	117.1	91.6
CO_2 in flue gas	%	4.2%	13.2%	13.2%
Rich solvent circulation	m^3/h	2845	7184	5622
Steam required	t/h	327	826	647
Solvent loss	kg/h	267	675	528
Cooling water required	m^3/h	18,434	46,543	36,425
Absorber	m dia	17.3	15.5	13.7
Direct contact cooler	m dia	17.3	n/a	n/a
Stripper diameter	m dia	8.2	13.1	11.6

(11) The DECC 2009 report again refers to coal fired plant and suggests 2.3 ha for CCS for 600 MWe and 0.083 ha for compressors. As described above a CCS on coal will be larger than a CCS on CCGT so these figures, corrected for the reduction from 600 MW to 500 MW represent the maximum area required for a CCS on CCGT, i.e. 1.986 ha.	See previous response to comments

SKM John Wearmouth (Jnr.), JRWearmouth@globalskm.com	
(1).I would suggest that more emphasis is placed on CCGT plant at the moment, given that these are the projects currently in the planning system and therefore being impacted by the guidance.	The report notes the paucity of data for CCGT and recommends a detailed engineering design project based on a generic CCGT be conducted
(2) I recommend that Imperial contacts potential suppliers of carbon capture plants (CCP), such as Fluor, Bechtel, MHI, Alstom, Siemens	This report aims to critically review the literature rather

and others, and asks if they can estimate the smallest amount of land on which they think they could provide a CCP for a 500 MW CCGT unit. Given that national infrastructure projects are at stake at a time when they are needed to be constructed at an unprecedented rate, no project should be refused permission unless it is certain that a CCP could not be accommodated on the site.	than conduct an engineering study; an important conclusion /recommendation is the need for a detailed engineering design project. We believe that this suggestion runs contrary to the spirit of the legislation.
(3) Regarding the suggested 20 % reduction in footprint for a CCP on a CCGT, i.e. from 3.75 ha to 3 ha for a “500 MW unit”, I would suggest that this is a far smaller reduction than is necessary.	See previous response to comments
(4) The document correctly points out that the IEA/Jacobs sizing was based on a 785 MW plant. This is a two-unit CCGT (2x GE9FA’s), and is also based on eight trains of carbon capture equipment	The authors agree that there is scope for size reduction with today’s technology. See previous response to comments
(5) The vast majority of CCR reports submitted thus far, and also detailed system designs worldwide, are based on one train of carbon capture equipment per CCGT unit	Fluor/Statoil feasibility studies report 15 m as a maximum diameter for absorption columns and on this basis assign 3 absorption trains for two GTs, the SKM report suggests 1 train per 500 MW GT.
(6) Given that the majority of the land required for a CCP is actually taken up by the space between the main items of equipment, having four trains per unit (i.e. the design on which the guidance is loosely based) results in a significant over-estimate of the land required	These concerns have been highlighted in the revised document
(7) It is commented in the document that the CCP on a CCGT requires more land than the CCP on a coal-fired plant. This is incorrect. While the absorber tower would need a larger diameter, the majority of the rest of the equipment, particularly the cooling towers (if required) would actually be larger for a CCP on a coal fired plant. This is due to the amount of CO_2 being processed being substantially higher, resulting in more solvent usage and more thermal treatment being required to remove the CO_2 from the solvent.	All assumptions should be stated to allow a reasonable comparison

Parsons Brinkerhoff Emily Agus, AgusE@pbworld.com	
(1) Due to the difference in capture requirements from coal-fired power plants and CCGT power plants, the land footprint requirements quoted in the Draft Report from coal-fired power plants with post-combustion capture are not applicable to CCGT power plants with post-combustion capture.	The report notes the paucity of data for CCGT and recommends a detailed engineering design project based on a generic CCGT be conducted
(2)[The draft report] fails to take into account the quantifiable improvements in terms of development in CCGT power plant technologies. For example, efficiency gains and technology developments mean that the same CCGT configurations and technology class Gas Turbines (GTs) on which Column 1 of Table 1 of the DECC November 2009 Guidance is based (when the space requirements are traced back to the IEA GHG Study 2005/1) are currently capable of generating around 850 to 925 MW, depending on the ambient site conditions and cooling system utilised. Additionally, an increase in electrical power output due to the efficiency gains and technology developments does not result in an equivalent relative percentage increase in 'CO$_2$ Produced' and indeed the 'Specific CO$_2$' production decreases. This is an important factor to consider in the sizing of ducts, heaters and other carbon capture equipment, and would imply that a direct scaling factor from Column 1 of Table 1 of the DECC November 2009 Guidance (which is based on the older GT technology) is inappropriate.	The authors do not propose a linear scaling factor, or any other factor, for relating power output to estimated land footprint for CCP. A reduction by 36 % is given as a conservative minimum reduction to correct for the basis of 500 MWe without capture. Reference to specific units/facilities, including number of absorption columns, strippers, cooling systems, dehydration and compression systems, etc. would eliminate ambiguity and allow a reasonable comparison to be drawn.
(3) PB find this conclusion to be overly simplistic and confusing. Is Imperial College London stating that: Table 1 in the DECC November 2009 Guidance should be amended to reflect the fact that the spacing for 'CCGT with post-combustion capture' is from a power plant with approximate net capacity before capture of 785 MWe, and that the space requirements for applications for CCGT with post-combustion are scaled from this (and still allow a 20 % reduction)?; Table 1 in the DECC November 2009 Guidance should be left, and space requirements should still be scaled on the basis of Table 1 representing 500 MW and be allowed to be reduced by up to 20%?; orSome other scaling factor?	We are grateful for the comments and the final document has been revised accordingly
(4) The IEA GHG Study 2005/1 (which is the basis for the original space requirement) states that "*the data provided is conservatively based on eight parallel CO$_2$ absorbers, compared to 3 and 2 in Fluor's and MHI's Studies*". Therefore, a reduction in the number of trains and sharing of common plant items allows for an initial layout	Reference to specific equipment, including number of absorption columns would eliminate ambiguity and

optimisation. Furthermore, Fluor have stated publicly [Econamine FG Plus Technology for Post-Combustion CO_2 Capture", presented at 11th meeting of the International Post-Combustion CO_2 Capture Network, 20 to 21 May, Vienna, Austria] that 20 m diameter absorbers are the design they are optimising the process for This size of absorber could treat the flue gases of more than one F-class500 MW CCGT train.Further studies undertaken by PB based on the Fluor 2005 Study have indicated that one carbon capture train per CCGT unit would allow for further layout optimisation and space requirement reduction.	allow a reasonable comparison to be made
(5) In addition, Column 1 of Table 1 does not allow for the fact that a CCGT capacity of 500 MWe (the basis of the DECC November 2009 Guidance) represents a single CCGT unit. However, the IEA GHG Study2005/1 (the basis of the original space requirements) is written on a CCGT capacity of 785 MWe representing two CCGT units. As such, the land footprint quoted in Column 1 of Table 1 of the DECC November 2009 Guidance is twice the area that the IEA GHG Study2005/1 concluded would be required for one CCGT unit. The Draft Report fails to make significant conclusions which would allow for the application of Table 1 of the DECC November 2009 Guidance to any of the Section 36 Consent applications currently with DECC / the EA. In line with the above reasoning, we believe that the spacing figures in Table 1 of the DECC November 2009 Guidance should not be used as a "*minimum*" space requirement. The space required for carbon capture equipment depends on a range of factors, including some site specific factors and, as such, is not easily scalable. Therefore the application of a single figure is unreasonable, and the layouts currently submitted with CCR Feasibility Studies should be considered on a case-by-case basis, with the assessment focusing on whether the layout submitted is feasible for that site, and recommendations being made on that basis rather on the basis of a minimum land footprint.If they are to be used at all, the figures in the DECC November 2009 Guidance (once corrected) are suitable a "worst case", such that if a developer has access to the area of land described in Table 1, it should not be necessary to submit a detailed layout, as there is evidently enough space.	We are grateful for the comments and the final document has been revised accordingly

Jonathon Marriott, RWE Npower Jonathan.Marriott@RWEnPower.com)	
(1) The author argues that :"layout optimisation for post-combustion retrofit to CCGT is constrained by the need to place the capture plant next to the CCCP due to the huge volumes of atmospheric flue gas with very low concentrations of CO2 (3–5 vol %)." (page 10).Comparing a 500MW CCGT unit with an 800 MW USCPF unit:Assume specific emission of coal is approx 0.7 Te/MWh Assume specific emission from CCGT is approx 0.4 Te/MWh	This point of view is expressed by Jacobs Consultancy (IEA 2005/1) and supported by GICCS (2010) The authors suggest that this point of view is based on economic limitations, rather

800MW coal gives 560 Te/h CO2 500MW CCGT gives 200 Te/h CO2 Assume 12% CO2 in flue gas for coal, 3.5% (conservative) in CCGT, therefore the CCGT unit will have approx (12/3.5) x (200/560) = 1.2 x the flue gas flow of the 800 MW coal unit. This means that the ductwork required for one 500 MW CCGT unit will need 1.2 x the cross sectional area of that required for an 800MW coal (ie width and height will increase by approx 10%). This is a large duct but not technically impossible, compared to what is being considered for 800 MW coal units.	technical feasibility; reference to specific units/facilities would eliminate ambiguity and allow a reasonable comparison to be drawn
(2) In Table 1 the ratio between USCPF post-combustion plot area requirement and the plot area requirement looks too high: on page 7 the DOE/NETL report is quoted: a USCPF post combustion plant had 2 acres for CO_2 compression and 1 acre for gas absorption. We can therefore assume that 1/3 of the plot is dedicated to absorption and 2/3 to CO_2 handling. Assuming the size of the absorption section is proportional to the volumetric flowrate of flue gas, and the CO_2 desorption and compression section is proportional to the flowrate of CO_2 being processed: Assume specific emission of coal is approx 0.7 Te/MWh Assume specific emission from CCGT is approx 0.4 Te/MWh 500MW coal gives 350 Te/h CO_2 785MW CCGT gives 314 Te/h CO_2 Therefore the CO_2 handling sections of the plant of the CCGT will have 0.9 x footprint of those for the coal station. Assume 12 % CO_2 in flue gas for coal, 3.5 % (conservative) in CCGT, therefore the CCGT will have approx 3.1 x flue gas flow of the coal station.Therefore area of 785 MW CCGT PCC plant is approx.: 0.9 x 2/3(CO_2 compression & desorption) + 3.1 x 1/3 = 1.6 x that of the 500 MW coal unit.– substantially less that the ratio of 4:1 in Table 1	The authors are grateful for these comments and the final document has been updated

URS Corporation Ltd **Dr Richard Lowe, Associate Director** <http://www.urscorp.eu/>	
(1)The basis for design between the referenced studies is very different regards net generating capacity and the information summarized does not detail the plot space requirements for specific portions of the facility (e.g. generation, power distribution, general support facilities such as cooling water systems, CO_2 capture, CO_2 Dehydration and Compression, CO_2 pipeline).	The authors agree and the final document has been updated to emphasise this important point
(2)It is important to understand which cases may have included modifications to upgrade the retrofit facility to maintain net power output, versus those that simply allowed loss of net output.	Reference to specific units/facilities and key assumptions would eliminate ambiguity and allow a reasonable comparison to be drawn
(3)Our experience has been that a retrofit of CCS is always site-specific and is therefore difficult to generalize. However, we also understand that with retrofits there is often limited space available for expansion. These retrofit efforts then require a unique approach to utilize the three dimensional space available, versus a more typical two-dimensional or single level amine capture system	We are grateful for the comments and the final document has been revised

design. In reference to a study we have completed, the multiple levels of operating platforms that are available inside existing structures have been utilized to achieve a safe, operable and maintainable facility – yet with a relatively small footprint.	
(4)URS CCS design for CCGT, net capacity without capture 900 MW, site dimensions for generation equipment = 24000 m^2, site dimensions for CO_2 capture and compression =20 000 $m^{2,}$ total 44 000 m^2	Awaiting clarification
(5)90% capture is a reasonable maximum to consider. An optimum recovery level may be between 85-90% depending on the technology chosen and on whether it is a coal-fired plant or a natural gas fired plant. For a coal fired plant, 90% recovery from say 12% CO_2 in flue gas allows treating to about 1 to 2% CO_2 remaining. For a gas fired plant, 90% recovery requires treating from say 4% to about 0.4% CO_2 remaining. The latter is more difficult to achieve without additional investment.	The authors are grateful for these comments
(6)Some polishing FGD may be advised but can often be incorporated into the quench column structure without adding plot space. The need for NOX treatment, if not already required for the existing facility, can be incorporated into the ducting between the gas turbines and the amine scrubbing systems without adding plot space.	The final document has been updated to emphasize this potential
(7)Most references cited do not address updated amine scrubbing	Awaiting clarification
(8)For equivalent power output, a coal-based plant produces about 75% of the volume of flue gas as a gas turbine. However, a coal fired plant will have say 12-15% CO_2 content, while a gas fired plant will contain 3 to 4% CO_2. The net result is that the coal-based plant will produce about 2.3 times the amount of CO_2. The ductwork, quench column and amine absorber are sized principally on flue gas volume, so these items would be about 85% to 90% of the cross sectional area of the gas-fired plant. However, the rest of the amine capture system will process more than 2.3 times the solvent circulation, require 2.3 times the amount of steam for regeneration, and must compress 2.3 times the amount of CO_2. At best these factors may offset so land use may be similar between the two options. However, it is more likely that the increase in amine footprint for a coal-based plant will exceed the reduction in flue gas handling equipment versus a gas-fired plant.	The authors are grateful for these comments and the final document has been updated
(9)This is a very key parameter that must be considered in any comparisons. A supplemental steam generating power system may need to be installed to support the added power requirements for the CO_2 capture and compression, and to provide the large amount of regeneration steam to the amine system. While we understand that the DECC guidance indicates that the use of additional power generation should be avoided, we feel that the likely advances in CCS between now and first commercial application are such that the power requirements of the future CCS plant may be substantially different from those calculated on today's technology. Similarly, any new build plant would have to be over-sized to account for the future CCS demand and then run at lower load (and efficiency) for the entire operating period between commissioning and the likely	This important point is included in the main document

later time-scale to eventual CCS installation	
(10)It is possible for the design concept to include the capability to add NOx reduction without requiring additional plot space, since there is ample space available in the required ducting lengths from generation to capture.	The final document has been updated to emphasize this potential
(11)Based on URS' extensive experience in recovering, purifying, dehydrating and compressing CO_2, our design for CCS is much different than the configuration proposed above, and versus that used for the DOE/NETL study. The approach described above appears to utilize reciprocating compressors with limited volume capacity to compress to above critical pressure. Then a pump is used to pressure the CO2 to the final pipeline pressure. This approach has been found to be less reliable, less safe, requires more plot space, and is much more costly than our preferred approach. Large capacity, multi-stage centrifugal compressors are used to compress the CO_2 all the way to the pipeline pressure. In this manner, the pumps, suction vessel and associated piping and controls are eliminated. This design approach has been proven successful in existing high-capacity CO2 compression systems. Two compressors can be provided per train to provide increased reliability. Plot space would be considerably reduced if this redundancy was not provided. The recent CCGT design required about 7300 MT/D total CO_2 capacity.	The report discusses the potential for technology improvements that may lead to footprint reductions and an increased scope for layout optimisation

Mott MacDonald Dr. Adina Popa-Bosoaga Thermal Generation Division,adina.bosoaga@mottmac.com; www.mottmac.com	
(1)One key conclusion from this comparison is that a meaningful **'minimum land requirement' for CCGTs in the CCR guidance** should specify the assumptions for areas quoted. **The layout** of the CCS plant and therefore the required area depends on many factors, and we have seen substantial differences between different studies and much more information is now available compared to when we carried out the study. An important broader point that we feel is currently inadequately reflected in the CCR guidance is that any layout is site specific and any footprint reference assumes a set of retrofit equipment, applicable to each scenario. Therefore the layout will depend on a number of factors including: - Availability of cooling water (e.g. seawater cooling vs. air-cooling); - Additional flue gas pre-treatment required before CO_2 capture; - Type and extent of CO_2 transport conditioning (e.g. shipping vs pipeline, pressure conditions, etc); - Column sizing (diameter, height, cross-sectional profile) for absorber and stripper - Use of dedicated auxiliary power and steam supply (e.g. CHP plant) for the Capture Plant, rather than full integration - Potential need for new utility supply equipment (CW, DW, compressed air etc) and stacks - Amine storage capacity (for peaking operation, accumulate lean	The authors agree and the final document has been updated to emphasise these important points

amine in off-peak hours?)	
(2) A significant plot space is required for construction. This is a very important aspect with respect to the overall construction cost and time schedule.	The authors agree that consideration be given to space required for construction/storage/equipment
(3)The layout also depends to some degree on how much land is available. Plants can often be squeezed into smaller areas if necessary but at a cost, so the regulator should be able to permit plants with smaller areas if the developer can provide evidence that they could build a capture plant in that area and they would be willing to accept any cost penalties.	The authors agree
(4)As concerning CCS applied to CCGTs, IEA document's (2005/1) referenced solution, adopts a conservative design with respect to column sizing, and therefore the number of capture trains and the space required, may not reflect current commercial offerings by CO_2 capture equipment providers. The IEA report includes eight trains of carbon capture equipment for a two unit CCGT. This approach is now outdated as with today's technology one CCP train can accommodate the flue gas from one CCGT unit, with major implications in terms of footprint and capital and operating costs. Rather than continuing to work with this configuration based on outdated column sizing, we would very much like to see the recommended footprints benchmarked against current commercial offerings.	See previous response to comments; The final document has been updated
(5)To remove the uncertainty around this subject and to clarify for a CCGT plant applicant what is the land required in order to demonstrate that the plant would be Carbon Capture Ready, we believe that the subject would benefit from a dedicated up-to-date analysis that clearly states its assumptions. Such a study would refer to the latest information from equipment manufacturers and would be based on calculations using commercial modelling software.	The authors agree, and this is one of the key recommendations

Dr Jon Gibbins/Dr Mathieu Lucquiaud , Edinburgh University m.lucquiaud@ed.ac.uk	
(1) In order to demonstrate that the proposed space is suitable and that development can be certified as CCR, operators should include outline site plans (drawings) in their application for s. 36 EA consent. The site plans, which will be public documents, will need to be more detailed than those currently submitted with s. 36 EA applications to enable the Environment Agency to advise Ministers that the proposed plant layout is suitable for subsequent CCS installation. The site plans should be sufficiently detailed to show: the footfall of the combustion plant the location of the capture plant; the location of the CO_2 compression equipment; the location of any chemical storage facilities; and the exit point for CO_2 pipelines from the site.	The authors agree, and this is one of the key recommendations
(2) Conceptual diagrams and a description, explaining how the space will used, should also be submitted. Basic calculations using the known volumes of CO_2 which will have to be processed could usefully be included in this description to justify the size of the	

vessels and processing equipment chosen.	
(3) Government envisages that the technical feasibility study for retrofitting CCS equipment will take the form of a written report and accompanying plant designs which: make clear which capture technology at the time of the s. 36 EA application the applicant thinks they might fit in the future; and provide sufficient detail to enable the Environment Agency to advise the Secretary of State on whether the applicant had sufficiently demonstrated there were no currently foreseeable technical barriers to subsequent retrofit of the declared capture technology.	The authors agree
(4) Applicants are directed to the IEA reference document 11 on capture technologies and to the advisory checklists (see Annexes 1A-C) when preparing their technical assessment of the feasibility of retrofitting carbon capture equipment	
(5) Access for construction: the footprint necessary for the capture/compression plant is obviously related to the layout of the power plant. You pointed it out rightly. Space and access for construction is, however, not necessarily included in the reports you reviewed and equally specific to the layout of the power plant. Additional space requirements is likely to be required around the capture plant, and could make a retrofit considerably more expensive to carry out-or in a worst case scenario lock-in the plant-if not accounted for. This can only be assessed on a site by site basis, but will tend to increase space requirements.	We have emphasized this point in the final document
(2)It is true that solvents developments can reduce the size of a certain part of the process through a higher carrying capacity. However, some future solvent developments aiming at reducing the <u>overall</u> electricity output penalty (and not steam consumption) will have a tendency to increase space requirements (additional water wash, lower steam pressure etc...). Because there is not a single solvent/technology, this may, in some cases, counterbalance equivalent gains made by layout optimisation.	The authors are grateful for the comments

Carlton Power, Mike Benson (mbenson@carltonpower.co.uk)	
(1)The assumptions involved in comparing the mass flow ratio of air/ CO2 between that of a CCGT exhaust, with that of a coal plant fitted with FGD and using pro rata per MW to give an estimate of layouts m2, could introduce some considerable inaccuracy in the estimation. In reality the actual layout of the CC plant will only be identified during the detailed design phase of the CCS conversion when the capture process is selected along with its typical footprint. This would then also need to be reviewed with the consideration of requirements for cooling; health and safety implications on vessels and equipment; hazardous area zone; CDM requirements; sizes of ducting; location and integration of CCGT and CCS plant and system modularisation.	We agree that relating footprint estimates and MWe is not straightforward and is dependent on the assumed equipment list, as well as site specific factors

(2)Given the limited technical information available and the potential error in any estimates of required area, we believe that more detailed design information and technology development is necessary before considering any change the recommendations at this time. This is prudent to avoid the risk of permitting CCR plant which ultimately cannot be converted.	This point of view is reflected in our recommendation for a detailed study based on a generic CCGT retrofit with specific focus on land footprint requirements

Appendix 2 Comments Received on 2nd Draft

Blythe Park Power John Wearmouth, john@blytheparkpower.co.uk; http://blytheparkpower.co.uk/index.html	
(1)We agree that all references to plant electrical capacity should be net of plant loads, before carbon capture	
(2)We agree that details to be provided in the CCR report should include the method of supply of steam (and electricity) to the CCS plant, the number of trains of CC, size of absorber and stripper columns, number of CO2 compressors, solvent/sorbent storage (based on usage rate of solvent/sorbent), and CO2 transport details.	
(3)A minor point, we consider that 'cooling water systems' should be reworded to 'cooling systems' as some CCGT plants will be air cooled.	We have changed the wording
(4)We do not understand the reference to 'additional flue gas treatment'. This may be referring to coal plant. For a CCGT there should be no requirement for removal of sulphur dioxide or dust	Additional flue gas treatment refers to any requirement relevant to coal or gas plant. We acknowledge that there are a range of perspectives in the literature and that there will be an economic trade-off in terms of the cost of new equipment vs. input of fresh solvent. The treatment could also include O_2 removal, for example.
(5)The references to SCR in the flue gas duct need to be revised. SCR operates at 300-400 deg C. The flue gas temperature leaving the gas turbine is above 500 deg C and in the duct after the HRSG is below 100 deg C. The SCR for a CCGT plant has to be installed in the HRSG where the temperature is in the range 300-400 deg C	The authors are grateful for the comment
(6)We see no need to reduce the NOx from the current levels to limit formation of amine salts in the CC process. However, we do consider it advisable to leave space for subsequently installing SCR in the HRSG in case the EU decide to reduce the NOx emission limit value from a CCGT even further at some future date	The authors are grateful for the comment
(7)We do not think that reference should be made to 90% capture. The percentage capture depends on the inlet flue gas temperature and the stripper operating temperature. Assuming a stripper temperature of 150 deg C and a recirculating quench system cooled by cooling towers could give an inlet flue gas temperature of 35 deg	The authors are grateful for the comment

C and possibly a percentage removal of 90%. If the cooling of the quench system is by air cooling then the flue gas temperature could be as high as 50 deg C and the percentage removal down to perhaps 85%. Note that this ignores any leakage across a gas/gas heater.	
(8)To reiterate our previous comment a CCS for a CCGT will NOT require more area than a CCS for a coal fired plant. As RWE state there is virtually no difference in the flue gas volume from a 500 MW CCGT and an 800 MW supercritical coal plant. Both CC plants will have to be located close to the generation plant and the fingerprint will be similar.	The authors are grateful for the comments, however suggest that there is insufficient evidence in the open literature to support this point of view
(9)With regard to the space required for construction, while we agree that some space is required, it is quite common for the contractor to be made responsible for providing this space off site. We think that the space required will only be available when a specific contractor is appointed and his construction methods determined. We, therefore, do not think that it is practical or necessary for this construction space to be detailed in the CCR report	The authors are grateful for the comment however acknowledge the range of perspectives in the literature
(10)The report does not appear to have taken into account Dr Agus' excellent point that an F technology gas turbine, in combined cycle mode would have an electrical output of about 380 MW in 2005, while the same machine would now have an output of 440 MW without any significant change in the gas burn, flue gas volume or CO2 produced. (Note these figures depend on the actual manufacturer and are only given here to show the change in output). Thus the size reduction should not be 500/785 but 500/880, ie not 36% but 43%. To this should be added the reduction brought about by the change from 8 to 2 steams	The report discusses that the original Jacob's study was based on conservative estimates and that today's technology would likely lead to footprint reductions by at least 36 % with increased scope for layout optimisation to up to about 50 % that can only be assessed site-by-site

Table A1. Approximate minimum land footprint for some types of CO_2 capture plant with correction for CCGT with post-combustion capture (assuming the same list of equipment for an output of 500 MWe without capture according to the IEA Report No. 2005/1)

<table>
<tr><th></th><th>CCGT with post-combustion capture</th><th>CCGT with pre-combustion capture*</th><th>CCGT with oxy-combustion capture</th><th>USCPF with post-combustion capture</th><th>IGCC with capture*</th><th>USCPF with oxy-combustion capture</th></tr>
<tr><td>Approx. net capacity without capture (MWe)</td><td>500</td><td>500</td><td>500</td><td>500</td><td>500</td><td>500</td></tr>
<tr><td>Site dimensions for generation equipment (m^2)</td><td>23 800</td><td>23 800</td><td>23 800</td><td>160 000</td><td rowspan="2">178 125</td><td>160 000</td></tr>
<tr><td>Site dimensions for CO_2 capture and compression equipment (m^2)</td><td>24 000</td><td>26 250</td><td>9 600</td><td>9 525</td><td>9 600</td></tr>
<tr><td>Total site footprint (m^2)</td><td>48 000</td><td>50 000</td><td>34000</td><td>170 000</td><td>180 000</td><td>170 000</td></tr>
</table>

* A correction for the reduced basis (from 785 MWe to 500 MWe) for CCGT with pre-combustion capture and IGCC with capture may be appropriate. However, the decision to scale down requirements must be made on the basis of an appropriately detailed engineering and literature study, focussing on these technologies.