



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

## Valuing Responsive Operation of Post-combustion CCS Power Plants in Low Carbon Electricity Markets

**Citation for published version:**

Errey, O, Chalmers, H, Lucquiaud, M & Gibbins, J 2014, 'Valuing Responsive Operation of Post-combustion CCS Power Plants in Low Carbon Electricity Markets', *Energy Procedia*, pp. 7471–7484.  
<https://doi.org/10.1016/j.egypro.2014.11.784>

**Digital Object Identifier (DOI):**

[10.1016/j.egypro.2014.11.784](https://doi.org/10.1016/j.egypro.2014.11.784)

**Link:**

[Link to publication record in Edinburgh Research Explorer](#)

**Document Version:**

Publisher's PDF, also known as Version of record

**Published In:**

Energy Procedia

**Publisher Rights Statement:**

© 2014 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

**General rights**

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

**Take down policy**

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact [openaccess@ed.ac.uk](mailto:openaccess@ed.ac.uk) providing details, and we will remove access to the work immediately and investigate your claim.





## GHGT-12

# Valuing responsive operation of post-combustion CCS power plants in low carbon electricity markets

Olivia Errey<sup>a\*</sup>, Hannah Chalmers<sup>a</sup>, Mathieu Lucquiaud<sup>a</sup>, Jon Gibbins<sup>a</sup>

<sup>a</sup> University of Edinburgh, School of Engineering, King's Buildings, Edinburgh, EH9 3JY, UK

### Abstract

This work considers the potential value in the additional flexibility of CCS post-combustion power plants gained by varying the operating CO<sub>2</sub> capture level. The continuous relationship between CO<sub>2</sub> capture level and the specific electricity output penalty is illustrated, and a new methodology is proposed for maximising net plant income through optimising the operating capture level. This methodology allows the plant to respond to electricity prices, fuel prices, and carbon reduction incentives including CO<sub>2</sub> prices and premium payments for low carbon electricity. The implications for flexible operation under different market scenarios are qualified, and the indicative value to plant operators is determined.

© 2014 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

Peer-review under responsibility of the Organizing Committee of GHGT-12

**Keywords:** Power plant operation; CO<sub>2</sub> capture; operating decisions; operating flexibility; CO<sub>2</sub> capture level

### 1. Introduction

Amine based post-combustion capture technologies were originally developed to operate in process industries under steady state conditions. To transpose these technologies into integrated power cycles, a number of different objectives must be considered for best process design and operating strategies. CCS power plants will be expected to generate power with low carbon dioxide (CO<sub>2</sub>) emissions, while maximising profits on an hourly basis by responding to meet the specific requirements of low-carbon electricity markets. Changes in relevant markets are regularly experienced by power plant operators and typically occur at different timescales, including rapidly varying prices for electricity, and slower changes in fuel prices and carbon reduction incentives such as carbon price. It is also expected that variations will increase with additional contributions to power supply from intermittent renewable energy sources. Studies are

\* Corresponding author. Tel.: +44-0131-650-7444.  
E-mail address: [o.errey@ed.ac.uk](mailto:o.errey@ed.ac.uk)

typically undertaken to minimize energy penalties and capital costs, or to maximise plant revenue for post-combustion CCS plants assuming steady state power plant conditions. This assumption is unlikely to be realistic for a large number of plants. Instead, as with current thermal power production, it is likely that power plants with post-combustion capture (and also other forms of CO<sub>2</sub> capture) will often need to operate responsively to market and ambient conditions to maximise profit on an hourly basis, while keeping within the technical limits of the full carbon capture and storage chain.

Previous work has primarily explored flexibility through capture plant bypassing and solvent storage [2-10]. This paper builds on that work to explore which factors are likely to be most important in determining maximum profit from given variations in the CO<sub>2</sub> capture level. In particular, it evaluates the additional revenue from the real-time optimisation of CO<sub>2</sub> capture levels and identifies methods that can be used to robustly identify options for maximising power plant revenue. Previous work has concentrated on carbon price as a mechanism for valuing the level of capture in a low carbon electricity market. This work further considers additional market case studies where zero-carbon electricity is eligible for a premium tariff, and additional revenues are evaluated and compared under these different market cases.

The quantitative analysis presented in this paper focuses on power plant load, and CO<sub>2</sub> capture from power plants operating in situations where electricity, carbon, and fuel prices are dynamic, shifting with market forces. In particular, the paper explores if and how deliberate variation of CO<sub>2</sub> capture level when a power plant is operating with CCS could be used to improve the economic performance of CCS power plants. The case study of power plants with integrated post-combustion capture, where the overall electricity output penalty of capture and compression (EOP) varies as a function of CO<sub>2</sub> capture rate, is used.

### Nomenclature

$E_C$	Cost of carbon emissions	£/tCO <sub>2</sub>
$E_E$	Wholesale market electricity selling price	£/MWh <sub>e</sub>
$E_{fuel}$	Fuel costs per thermal input	£/MWh <sub>th</sub>
$E_{PE}$	Premium electricity price for zero carbon electricity	£/MWh <sub>e</sub>
$\epsilon$	Fuel specific CO <sub>2</sub> emissions factor	tCO <sub>2</sub> /MWh <sub>th</sub>
$\eta_{base}$	Efficiency of base power plant operating without CO <sub>2</sub> capture	MWh <sub>e</sub> /MWh <sub>th</sub>
$\eta_{cap}$	Efficiency of base power plant operating with CO <sub>2</sub> capture	MWh <sub>e</sub> /MWh <sub>th</sub>
$anc$	Electricity output penalty for ancillary equipment operation during capture plant bypass	kWh <sub>e</sub> /tCO <sub>2</sub>
$c_x$	Fraction of CO <sub>2</sub> captured from flue gas; operating capture level	–
$c_{xopt}$	Fraction of CO <sub>2</sub> captured from flue gas to maximise cash flow; optimum capture level	–
$E_{CO_2}$	Electricity exported with a CO <sub>2</sub> intensity	MWh <sub>e</sub>
$E_0$	Electricity exported defined as zero carbon	MWh <sub>e</sub>
$EOP(c_x)$	Electricity output penalty at a given capture level	kWh <sub>e</sub> /tCO <sub>2</sub>
$f$	Rate of energetic input from fuel	M
$vc_{base}$	Specific variable costs of power plant per unit of electricity produced	£/MWh <sub>e</sub>
$vc_{cap}$	Specific variable costs of capture plant per tonne of CO <sub>2</sub> captured and compressed	£/tCO <sub>2</sub>
$SGI_{CO_2}$	Standard electricity grid counterfactual CO <sub>2</sub> intensity	kgCO <sub>2</sub> /MWh <sub>e</sub>
$SRNCF$	Short run net operating cash flow	£/hr

### Subscripts

$case\ 1$	Case study 1
$case\ 2$	Case study 2
$case\ 3$	Case study 3
$bp$	Capture plant bypass

### *1.1. Flexible operation of post-combustion carbon capture through varying CO<sub>2</sub> capture level*

It is important to carefully assess the technical options for operating thermal plants flexibly with CCS technologies, since many of the technologies being considered for CCS applications were originally developed for steady state operation in process industries [1]. However, operating with CCS could also increase options for flexible power plant output, including by reducing or bypassing carbon capture processes and converting the energy that is no longer used for CO<sub>2</sub> capture and compression into electricity, as proposed by several studies [2-10]. The energy penalty incurred by operating with CO<sub>2</sub> capture is a significant percentage of the net plant output. Taking the example of modern amine capture technologies used in a post-combustion capture application, a 7-11 %-point penalty reduction is typical after 90% of the flue gas CO<sub>2</sub> is captured and compressed [1, 11, 12], which equates to approximately 20% of output for a modern USC coal plant or 15% of output for an efficient NGCC. If CCS power plants operate at a lower capture level, or bypass the capture unit completely, then that energy penalty can be converted to electricity exportable to the grid to increase electricity sales if the plant has been designed to accommodate the changes in steam flow associated with this change in operations.

The primary revenue stream for power plants is the sale of electricity. When operating with an electricity output penalty from CO<sub>2</sub> capture and compression, there is, therefore, a significant potential revenue diversion. Conversely, a plant profitably operating CO<sub>2</sub> capture in a low carbon energy market must have an incentive to capture CO<sub>2</sub>, either through fiscal penalties for emitting CO<sub>2</sub> (e.g. a carbon price), or through a premium payment for low carbon electricity. The net plant income, accounting for both revenue generation from electricity exports and net economic gains from CO<sub>2</sub> capture, therefore, depend on the market prices of wholesale electricity, as well as CO<sub>2</sub> and/or premium low carbon electricity payments. The balance of these market prices provides a direct relationship between plant net income and the level of CO<sub>2</sub> capture operated.

Importantly, electricity is not a fixed price commodity; there are times of high demand/supply ratio when electricity is highly valuable, and vice versa, as reflected in electricity market pricing structures. The value of CO<sub>2</sub> emissions abatement will also likely vary over time as CO<sub>2</sub> reduction targets become tighter in line with scientifically advised greenhouse gas reduction targets, e.g. [13]. The balance of these market influences on the plant will dictate the operating conditions for maximum net plant income. This is represented in Figure 1.

Power plants with CCS are typically designed for a specific capture level, determined by a cost trade-off between maximising CO<sub>2</sub> removal and minimising capital expenditure and operating costs based on long term assumptions. This level of capture is a design point, dictating the dimensions and configuration of capture units, and is described here as the design capture level. The operating capture level by contrast describes the real time percentage of CO<sub>2</sub> captured and compressed. The operating capture level and the design capture level are only equivalent at steady state operations that meet the plant design point. The operating capture level can respond flexibly to market and other environmental stimuli to control plant electricity output and maximise net plant income. Capture plant response to variation in capture levels is specific to the configuration and technology of each capture unit.

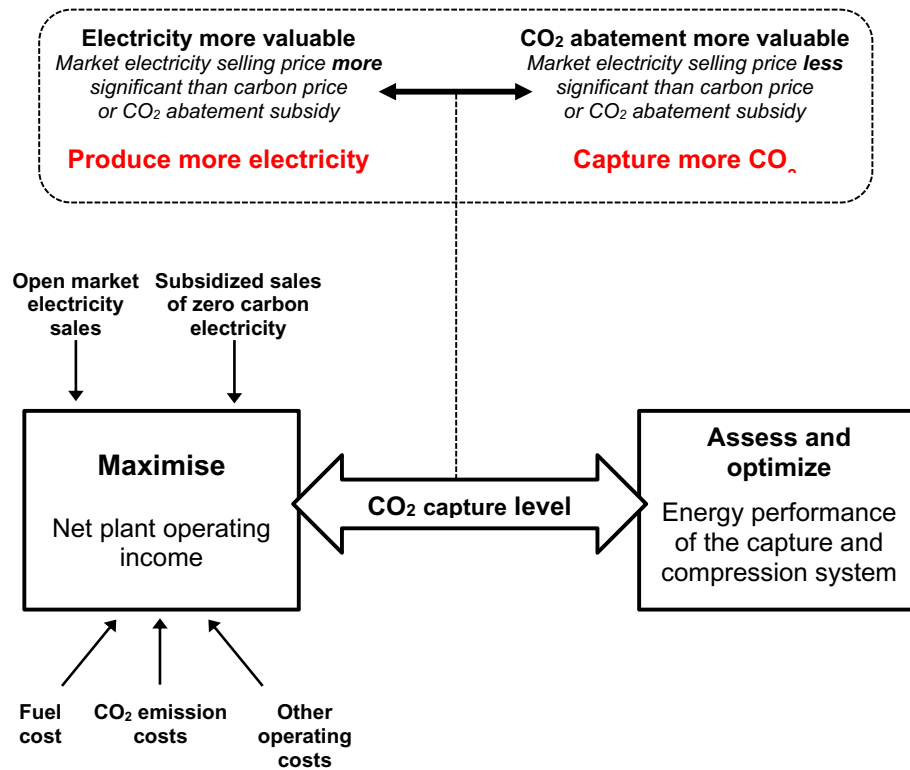


Figure 1. A schematic diagram illustrating the concept of maximising net plant operating income for power plants with CCS through variation in plant capture level in response to market incentives, with respect to individual plant performance

This work builds on the previous studies [2-10] by considering a continuous relationship between the plant electricity output penalty and broad operating capture level range, rather than considering design point capture and plant bypass only, or discrete full and minimum capture level scenarios. Recent studies [14, 15] consider a continuous range of capture levels to illustrate plant operating costs related to capture level, but their work stops short of proposing a methodology to maximise net plant income by optimising the capture level, as presented in this work.

### 1.2. Market incentives for CO<sub>2</sub> emission abatement

This work considers additional market incentives for low carbon electricity systems beyond the concept of carbon price. Investment decisions based on unstable carbon markets are difficult, and instead alternative fiscal methods for incentivising low carbon electricity may be used for short to mid-term CCS project financing. The three incentive cases considered in this paper are summarised in Table 1. Case 1 considers an open wholesale electricity market with a carbon price only. Cases 2 and 3 consider scenarios where plants operate within wholesale electricity and carbon markets, with additional premium electricity price payments made available for zero carbon electricity generation. In both these Cases a low, fixed price for carbon is assumed. The difference between Cases 2 and 3 is how 'zero carbon electricity' eligible for the premium price is defined. In Case 2, zero carbon electricity is assumed to be the net exported

electricity proportional to the CO<sub>2</sub> capture level, as defined in Equation 1.

$$E_{0(\text{case 2})} = f \eta_{\text{cap}} c_x \quad (1)$$

$E_0$  is the zero carbon electricity generated,  $f$  the fuel energetic input rate,  $\eta_{\text{cap}}$  the net efficiency of the plant after capture, and  $c_x$  the capture level. From Equation 1, it follows that the remaining electricity exported, eligible for sale only at wholesale electricity prices, is defined as Equation 2, where  $E_{\text{CO}_2}$  is electricity exported with a CO<sub>2</sub> intensity.

$$E_{\text{CO}_2(\text{case 2})} = f \eta_{\text{cap}} (1 - c_x) \quad (2)$$

This Case 2 definition implies that an equivalent plant without capture is used as a counterfactual. Different CCS power plant operating the same capture level, but emitting different amounts of CO<sub>2</sub>, depending on fuel carbon intensities and net plant efficiencies, would, therefore, be eligible for the same level of carbon abatement incentives.

In Case 3, CO<sub>2</sub> emitted by a plant is compared with an accepted, defined, standard grid counterfactual CO<sub>2</sub> emission intensity (SGI). The total CO<sub>2</sub> emissions of the operating CCS plant can be compared to this counterfactual to determine the amount electricity generated at this standard grid CO<sub>2</sub> emission intensity, defined in Equation 3. This electricity would be valid for sale on a wholesale market.

$$E_{\text{CO}_2(\text{case 3})} = f \frac{\epsilon(1-c_x)}{\text{SGI}_{\text{CO}_2}} \quad (3)$$

The remainder of the electricity exported by the plant can then be defined, across all plant, as zero-carbon electricity valid for premium low carbon electricity payments. See Equation 4.

$$E_{0(\text{case 3})} = f \eta_{\text{cap}} - f \frac{\epsilon(1-c_x)}{\text{SGI}_{\text{CO}_2}} \quad (4)$$

This work considers the short run implications of operating with these three market incentives. Long term contracts are not considered in this analysis.

Table 1. Case studies of market incentives for CO<sub>2</sub> emission abatement

	<b>Case 1 Carbon price only</b>	<b>Case 2 Proportional premium</b>	<b>Case 3 Standard counterfactual</b>
<b>Description</b>	A wholesale electricity market with carbon prices for CO <sub>2</sub> emissions	A wholesale electricity market with a carbon price plus premium payments for electricity generated proportional to CCS plant operating capture levels	A wholesale electricity market with a carbon price plus premium payments for electricity generated beyond the output equivalent of a plant operating a standard grid CO <sub>2</sub> intensity generating the same mass of CO <sub>2</sub>
<b>Eligible for carbon price</b>	Yes	Yes	Yes
<b>Sales of electricity to the wholesale electricity market</b>	All electricity exported	Remainder of electricity exported	Electricity generated at standard grid CO <sub>2</sub> intensity counterfactual
<b>Sales of zero carbon electricity at a premium</b>	None	Electricity exported proportional to operating capture level	Remainder of electricity exported

### 1.3. Illustrative power plant operating post-combustion carbon capture

To demonstrate the concepts described in this work, an example of an illustrative CCS power plant is used: a supercritical coal plant operating with an aqueous MEA post-combustion capture unit designed to capture 90% CO<sub>2</sub>. The plant is assumed to be configured with a single train absorber and compression system. Techno-economic parameters of this illustrative plant are given in Table 2. The power island is assumed to operate at full load with a constant fuel input.

Table 2. Techno-economic parameters of illustrative power plant operating post-combustion carbon capture

Parameter	Units	Value
Rate of energetic input from fuel ( $f$ )	MW <sub>th</sub>	2000
Base plant efficiency ( $\eta_{base}$ )	-	0.4
Fuel specific emissions factor ( $\epsilon$ )	tCO <sub>2</sub> /MWh <sub>th</sub>	0.341
CO <sub>2</sub> capture and compression efficiency penalty at 90% capture	%-points	9
CO <sub>2</sub> capture and compression electricity output penalty at 90% capture	kWh <sub>e</sub> /tCO <sub>2</sub>	294
Variable costs of base plant ( $vc_{base}$ )	\$/tCO <sub>2</sub>	4 [11]
Variable costs of capture plant ( $vc_{cap}$ )	\$/MWh <sub>e</sub>	5 [11]

## 2. The relationship between the electricity output penalty of CO<sub>2</sub> capture and compression, and the operating capture level

To quantify the energy loss associated with CO<sub>2</sub> capture and compression, the metric of specific Electricity Output Penalty (EOP) is introduced, defined as the total reduction in electricity exported due to the capture and compression of given mass of CO<sub>2</sub>.

Specific EOP is a useful metric for techno-economic analysis as it quantifies the energy penalty for a given mass of CO<sub>2</sub> captured as electricity which would otherwise be sold to the grid for income. By considering the EOP of a capture process at given conditions, opportunities for flexible power provision in the form of responsive changes to electricity export can be quantified from forced EOP variations through capture plant operating decisions, independent of the main power plant. EOP is specific to the configuration and technology of each capture unit, and dependent upon the CO<sub>2</sub> concentration of the flue gas and the CO<sub>2</sub> capture level, but independent of the base power plant efficiency; an inefficient power plant can have the same EOP as a more efficient one if the capture process and flue gas compositions are equivalent [16].

EOP can be calculated from the net power output losses and the mass flow rate of CO<sub>2</sub> captured. Taking the example of integrated aqueous solvent based post-combustion capture; the net power loss is described as the sum of four components as described below and in Equation 5:

1. Turbine power output losses as a result of the diversion of steam to the solvent reboiler
2. Electrical power to drive the CO<sub>2</sub> compression train
3. Electrical power to drive induction fans situated immediately before the post-combustion capture unit
4. Electrical power to drive solvent pumps and other small ancillary equipment

$$EOP \left( \frac{kWh_e}{tonne} \right) = \frac{\text{loss of generator output} + \text{compression power} + \text{fan power} + \text{ancillary power} (kW_e)}{\text{mass flow rate of CO}_2 \text{ captured and compressed} \left( \frac{tonne}{hr} \right)} \quad (5)$$

These EOP components will be differently affected by changes to operating capture levels, and can together be used

to analyse the energetic response of the whole CO<sub>2</sub> capture process.

Using the post-combustion capture plant example described in Section 1.3, an illustrative relationship between the specific EOP and operating capture level is given in Figure 2. This curve shows EOP increasing rapidly above the design capture level as increasingly lean loadings are required to achieve the higher capture levels, increasing reboiler duty and significantly decreasing steam flow to the power cycle. The compression units and pumps also move away from design point reducing in efficiency and slightly increasing the specific EOP.

Operating at lower capture levels leads to a reduction EOP as reboiler duty and subsequent steam diversion is reduced due to lower solvent flow rates and lower sensible and latent heat requirements. However, this reduction is partly offset by decreases in mechanical efficiencies of the pumps, fan and compressors away from design point, and then cancelled out at lower capture levels once CO<sub>2</sub> recycling is required in the compression train to avoid choke conditions. CO<sub>2</sub> recycling is assumed to operate at 75% of the compressor design load, equivalent to an inflection point at 68% capture. There will also be a minimum stable capture level associated fluid distribution in the columns, reboiler levels, and pump turn down limits. In this example this minimum stable load is assumed to be 20%. Turn down beyond the minimum stable operation moves to a full bypass of the capture plant. Figure 3 provides an illustration of the potential change in plant output at a given capture level corresponding to the relationship given in Figure 2.

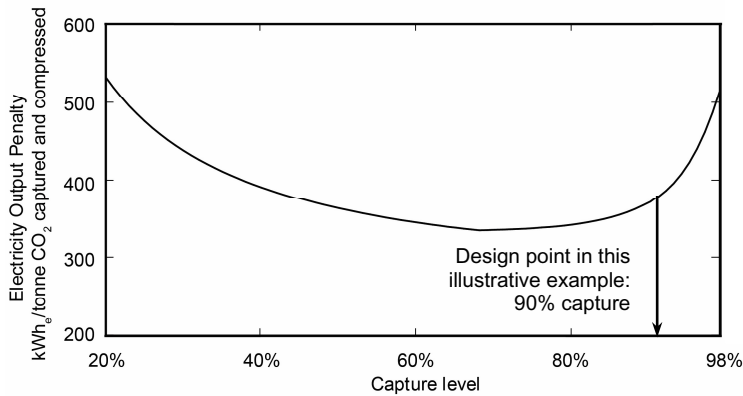


Figure 2. Illustrative example of the variation in Electricity Output Penalty with capture levels ranging from 20% - 98%. This relationship is plant specific varying with configuration and conditions of each CCS plant. This illustrative example represents the

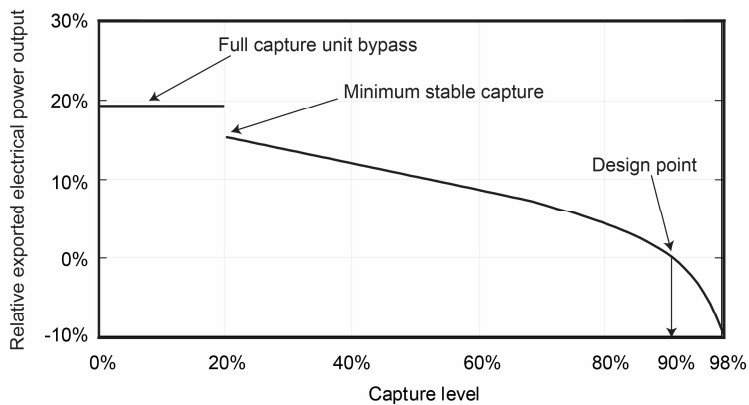


Figure 3. Relative change in exported electricity output potential for off-design point capture level operation of the illustrative capture plant example represented in Figure 2.



The overall plant efficiency can, therefore, be calculated with EOP as a function of capture level. The capture unit percentage-point efficiency penalty is the product of the mass of CO<sub>2</sub> generated per thermal unit of energy (defined as the fuel specific CO<sub>2</sub> intensity  $\epsilon$ ), the fraction of this CO<sub>2</sub> captured, and the penalty in electrical units of energy for a given mass of CO<sub>2</sub> captured and compressed (EOP). This is defined in Equation 6.

$$\eta_{cap} = \eta_{base} - EOP(c_x)c_x \epsilon \tag{6}$$

For a power plant operating post-combustion capture, the relationship between operating capture level, net plant efficiency, electricity export and CO<sub>2</sub> emitted is illustrated in Figure 4.

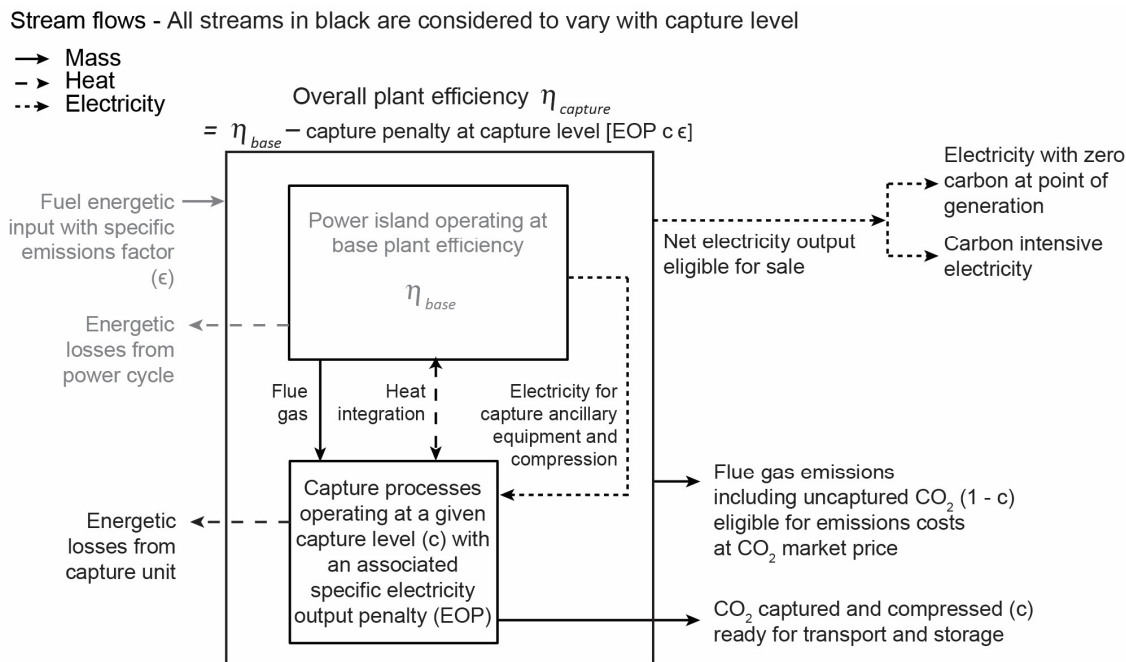


Figure 4. Schematic of the relationship between plant capture level and overall plant efficiency, net electricity output, EOP, CO<sub>2</sub> emissions, revenue streams and other costs for a post-combustion capture plant

### 3. A methodology to maximise short run net cash flow by optimising operating CO<sub>2</sub> capture level

#### 3.1. Defining short run net operating cash flow for power plants operating with carbon capture in low carbon electricity markets

Short run net operating cash flow (SRNCF) of a power plant with carbon capture can be defined as the difference between the plant revenue and the short run marginal cost (SRMC) for a given time period of operation, often covering a single set of market conditions. SRMC is the operating cost of a plant not including fixed costs that are independent of whether a plant operates or not. For example, costs associated with the repayment of capital are fixed costs. When SRNCF is positive, operating the plant generates earnings, and vice versa; continuing to run the plant when SRNCF is negative will result in the operator losing money. Zero or negative values of SRNCF will generally lead to the plant being turned off where feasible (a plant might be operated at low load if two-shifting plant starting up shortly after a shutdown would not be an attractive operating pattern for a particular plant, but this is outside the scope of this paper).

SRNCF differs from Levelised Cost of Electricity (LCOE), where long term assumptions of operating patterns and costs are made to provide an indication of average revenue necessary to return investment. As described in detail by Joskow [17], calculation of a levelised, annualised, cost considers electricity as a priced homogeneous product rather than a service with a range of values depending on when and how it can be dispatched. The associated profitability of a responsive, dispatchable power generator is generally not fully represented by a single value of its electricity cost based upon assumptions of lifetime operating costs and average load factor. Power generation that can respond at times of high demand can be expected to benefit from high electricity prices, potentially significantly increasing plant revenue, as income increases outweigh any increase in operating costs. It is, therefore, within the interest of the plant operators to maximize SRNCF through operating decisions in response to market forces.

The general equation for SRNCF for a power plant with CO<sub>2</sub> capture is defined in Equation 7.

$$SRNCF = \text{income from electricity sales} - \text{fuel costs} - \text{carbon emission costs} - \text{carbon capture variable opex} - \text{base plant variable opex} \quad (7)$$

SRNCF is further defined in terms of capture level, as a function of EOP, market conditions and other costs associated with SRMC, for the three cases considered in this work in Equations 8-10. Equations 9 and 10 use the definitions of zero carbon electricity given in Equations 1-4.

SRNCF Case 1 (carbon price only):

$$SRNCF_{(case\ 1)} = E_E f [\eta_{base} - EOP(c_x)c_x \epsilon] - E_f f - vc_{cap} f c_x \epsilon - E_c f (1 - c_x)\epsilon - vc_{base} f \eta_{base} \quad (8)$$

SRNCF Case 2 (proportional premium):

$$SRNCF_{(case\ 2)} = E_E f [\eta_{base} - EOP(c_x)c_x \epsilon](1 - c_x) + E_{PE} f [\eta_{base} - EOP(c_x)c_x \epsilon]c_x - E_f f - vc_{cap} f c_x \epsilon - E_c f (1 - c_x)\epsilon - vc_{base} f \eta_{base} \quad (9)$$

SRNCF Case 3 (standard counterfactual):

$$SRNCF_{(case\ 3)} = E_E f \frac{\epsilon(1-c_x)}{SGICo_2} + E_{PE} f \left( [\eta_{base} - EOP(c_x)c_x \epsilon] - \frac{\epsilon(1-c_x)}{SGICo_2} \right) - E_f f - vc_{cap} f c_x \epsilon - E_c f (1 - c_x)\epsilon - vc_{base} f \eta_{base} \quad (10)$$

When the overall emissions intensity of the plant is equal to or greater than the standard grid CO<sub>2</sub> intensity, there is no export of zero carbon electricity and the definition of SRNCF for Case 3 (standard counterfactual) reverts to that of Case 1 (carbon price only). This is defined in Equation 11.

$$\frac{\epsilon(1-c_x)}{SGICo_2} \geq [\eta_{base} - EOP(c_x)c_x \epsilon] \Leftrightarrow SRNCF_{3(cx)} = SRNCF_{1(cx)} \quad (11)$$

$E_E$  is the wholesale electricity price and  $E_{PE}$  the premium price for electricity defined as zero carbon,  $E_f$  and  $E_c$  are the market price for fuel and carbon emissions respectively,  $vc_{cap}$  and  $vc_{base}$  the variable costs associated with operating the capture plant and the base plant, and  $f$  the energetic input of fuel.  $SGICo_2$  is a standard counterfactual grid CO<sub>2</sub> intensity with which to compare plant emissions across the electricity market,  $c_x$  is the plant operating capture level,  $EOP(c_x)$  the electricity output penalty at the operating capture level,  $\eta_{base}$  the base plant efficiency,  $\epsilon$  the fuel specific emission factor.

### 3.2. Defining short run net operating cash flow for power plants operating with capture plant bypass

Full capture plant bypass is defined as a diversion of the total quantity of flue gas entering the capture unit directly to the stack, fully bypassing the capture unit thereby enabling electricity previously utilised in the capture plant to be exported to the grid. However, to enable a faster start up after a full bypass and allow the plant to take advantage of fast changes to electricity prices, it is likely that at least some ancillary equipment will be maintained in operation during a full bypass. For the quantitative analysis reported in this paper, the energy associated with this ancillary equipment is modelled as an illustrative EOP of 1 %-point (Chalmers, 2010) [18].

As there is no low carbon electricity generated during capture plant bypass the definition of SRNCF at bypass is the same for all three market cases, given in Equation 12.

$$SRNCF_{bp} = \epsilon_E f [\eta_{base} - anc \epsilon] - \epsilon_{fuel} f - \epsilon_c f \epsilon - v_{c_{base}} f \eta_{base} \quad (12)$$

Where  $anc$  is a fixed penalty for ancillary equipment operating during bypass.

### 3.3. Methodology for optimising operating capture level

To determine the optimal operational capture level, a maxima for short run net operating cash flow is found from the root of the differential of short run net cash flow with respect to capture level, as shown in Equation 13.

$$c_{xopt} = \frac{dSRNCF}{dc_x} = 0 \quad (13)$$

Where  $c_{xopt}$  is the optimised capture level with respect to SRNCF.

This root is confirmed as a maxima, and also constrained by inequality X as in this work a minimum stable capture level is assumed at 20% capture and a capture level of 98% used as an upper feasible capture limit.

$$0.2 \leq c_x \leq 0.98 \quad (14)$$

Analytical solutions for Equation 13, providing a parametric equations for optimum capture level operation in each Case, are given below in Equations 15 – 17.

Case 1 (carbon price only):

$$c_{xopt} (case 1) = \left( \frac{\epsilon_{CO_2} - v_{cap}}{\epsilon_E} - EOP(c_{xopt}) \right) \frac{dc_{xopt}}{dEOP(c_{xopt})} \quad (15)$$

Case 2 (proportional premium):

$$c_{xopt} (case 2) = \frac{\epsilon_{CO_2} - v_{cap} + (\epsilon_{EP} - \epsilon_E) \frac{\eta_{base}}{\epsilon} - \epsilon_E EOP(c_{xopt})}{\epsilon_E \frac{dEOP(c_{xopt})}{dc_{xopt}} + (\epsilon_{EP} - \epsilon_E) \left( c_{xopt} \frac{dEOP(c_{xopt})}{dc_{xopt}} + 2EOP(c_{xopt}) \right)} \quad (16)$$

Case 3 (standard counterfactual):

$$c_{xopt} (case 3) = \left( \frac{\epsilon_{CO_2} - v_{cap} + \frac{\epsilon_{EP} - \epsilon_E}{SGIC_{CO_2}}}{\epsilon_{EP}} - EOP(c_{xopt}) \right) \frac{dc_{xopt}}{dEOP(c_{xopt})} \quad (17)$$

Equations 14-16 illustrate that the operating capture scenario for maximum SRNCF will balance changes in electricity output penalty against financial benefits for decreasing the amount of CO<sub>2</sub> emitted.

Once the optimum capture level has been determined it is also necessary to determine whether it is optimal to operate with a full capture plant bypass or with CO<sub>2</sub> capture. This decision is made by comparing SRNCF at optimum capture with SRNCF with bypass. In this study, when these are equal or when SRNCF at bypass exceeds the SRNCF at the optimum capture level, a plant bypass operating regime is assumed as illustrated in Equation 18.

$$SRNCF_{bp} \geq SRNCF_{(c_{opt})} \Leftrightarrow \text{Operate bypass} \quad (18)$$

Operating at this optimal operating capture level or bypass regime provides a CCS power plant with net maximum short run net operating cash flow for given the market conditions.

### 3.4. Discussion and illustrative results

It is important to note that the optimum capture level is independent of fuel price when the base plant operates at full load as fuel input is constant. Optimum capture level is also independent of base plant efficiency, except in Case 2 where net plant CO<sub>2</sub> emissions are compared against the base plant emission intensity (a function of base plant efficiency). Variable capture costs are assumed to be constant in this work since they are usually small compared with carbon prices. These equations therefore imply that the optimum capture level will depend on the ratio between carbon capture incentives (carbon price, premium electricity price difference) and electricity prices, with high carbon prices incentivising high capture levels and high market electricity prices incentivising lower capture levels. Equation 19 describes this in a general equation for optimal capture level, taking from equations 15 - 17.

$$C_{xopt} = \frac{\frac{\text{Financial opportunity of capture}}{\text{Financial opportunity of electricity sales}} - \text{Electricity output penalty of capture}}{\text{Change in electricity output penalty with the capture level}} \quad (19)$$

The impact of the ratio of capture incentives to wholesale electricity price is tempered by both the absolute and the change in EOP with capture level; the nature of the plant's energy loss response to changes in capture level. Higher absolute values of EOP will lead to lower optimal capture levels. This can be explained as capture levels with higher energy losses will produce less available electricity to take advantage of the higher electricity prices. Finally, at high capture levels, beyond the design point typically above 90%, a very steep increase in EOP with capture level is likely to occur as the capture plant is operating increasingly closer to the thermodynamic limits for separation work between gases. This implies that at a given capture level, significantly higher than the design point in the 90-98% range, optimal operation occurs with a shallow change of the marginal increase in EOP with capture levels.

Figure 5 shows a set of decision diagrams of optimum operating conditions for a range of carbon, electricity and fuel prices for each of the Cases considered in this study, based on Equations 8 – 18. The financial implications of this methodology for optimal operation are demonstrated, with indicative total and relative cash flow gains given in overlay contours for the illustrative example used in this paper.

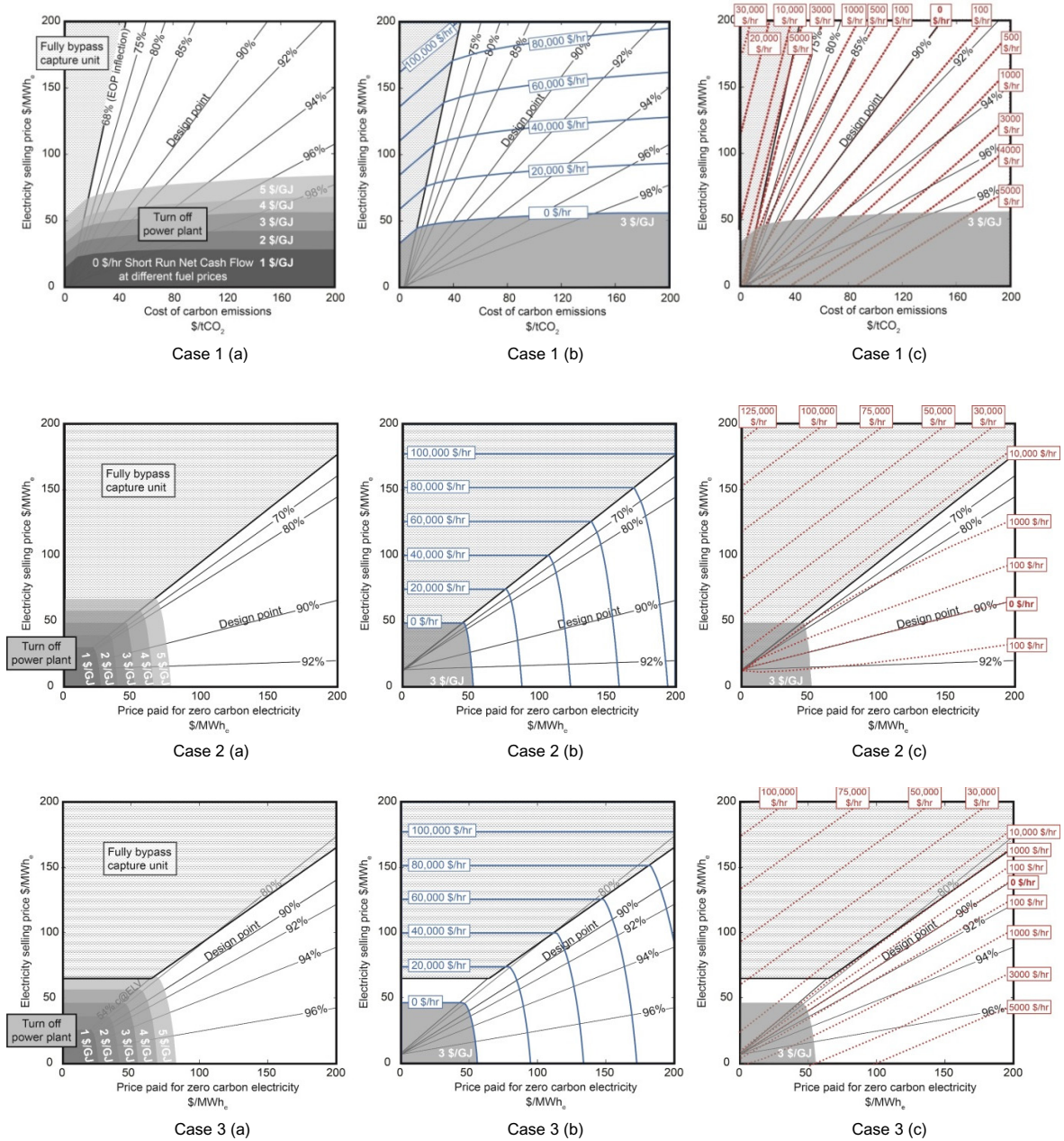


Figure 5. Illustration of optimum operating capture plant scenarios to maximise short run net operating cash flow at different electricity selling prices, CO<sub>2</sub> emission prices and fuel prices for the three low carbon electricity market Cases detailed in Table 1. Operating options include optimal capture levels (black contours), capture plant bypass (hashed region) and the option of turning off the power plant corresponding to a short run net cash flow of zero or below (solid shaded regions).

Figures (a) illustrate the optimum operating conditions for each case study. Figures (b) indicate the SRNCF corresponding to the optimum operating decisions for each case, shown in the overlay solid contour lines. A single fuel price of 3 \$/GJ and a CO<sub>2</sub> price of 18 \$/tCO<sub>2</sub> is assumed. Figures (c) indicate the additional short run net cash flow to be gained operating at optimal capture conditions compared with operating at a fixed 90% capture design point, shown in the overlay dashed contour lines. A SGI of 450 kgCO<sub>2</sub>/kWh is assumed, and again a single fuel price of 3 \$/GJ and a CO<sub>2</sub> price of 18 \$/tCO<sub>2</sub> is assumed.



#### 4. Conclusion

This paper explores the potential for power plants with CO<sub>2</sub> capture to improve their economic performance by operating flexibly in response to varying electricity prices and also in response to different incentives to encourage operation of CO<sub>2</sub> capture (or penalising CO<sub>2</sub> emissions, if CO<sub>2</sub> is not captured). An illustrative example of amine-based post-combustion capture at a coal-fired power plant is used to explore a range of operating operations for three different approaches to incentivising the use of CO<sub>2</sub> capture.

The analysis reported in this paper characterises power plant performance with CO<sub>2</sub> capture using an electricity output penalty (EOP), which is converted into a loss of potential revenue, for a range of electricity, carbon and fuel prices. The case study results show that when this ‘opportunity cost’ is balanced against costs for emitted CO<sub>2</sub> it is likely that operating revenues from CCS power plants will sometimes be improved by operating a post-combustion capture unit off-design (e.g. at a higher or lower capture level than the design point - or sometimes not at all).

Decision diagrams are presented which illustrate optimum capture rates under different price scenarios, and in different market case studies. The economic impact of optimisation under these different scenarios can also be quantified. Illustrative figures are reported to demonstrate the value of alternative options for flexible plant operation.

This paper shows that the inherent volatilities in electricity value (through varying electricity demand/supply balance) and carbon emission costs also lead to continuous adjustment of capture levels being necessary to achieve cost-effective low carbon electricity supply. In particular, plants seeking to maximise their returns in the market may operate at capture levels that are different from their nominal design values. For many of the scenarios considered in this paper, relatively high levels of capture are economically preferable, with capture rates above the design capture rate being preferred in situations where relatively low electricity prices are combined with strong incentives to produce low carbon electricity. There are, however, also situations where operating CO<sub>2</sub> capture with capture levels substantially below the design capture rate are preferred. In extreme cases (high electricity prices and weak incentives for low carbon electricity production) this leads to capture plant bypass being the preferred operating mode.

These findings have implications for plant design and operating strategies since they suggest that in at least some jurisdictions electricity utilities would benefit from CO<sub>2</sub> capture plant (and associated power plant) designs that include features to facilitate reasonably efficient operation across a broad range of capture levels. Such designs might differ from designs optimised for operation only at a single design point. This could include both detailed engineering analysis of potential plant configurations and ‘whole systems’ analysis to improve understanding of the likely profitability of different proposed modifications to CO<sub>2</sub> capture plant design and operation. For example, power plants with multiple trains of CO<sub>2</sub> capture and compression could have very different shapes of EOP curve, which may make lower capture levels more economically attractive (e.g. in situations where the choice between capture plant bypass and operating with CO<sub>2</sub> capture is marginal).

It is also important to note that bypass and subsequent additional electricity export is dependent upon the ability of the plant to operate without CO<sub>2</sub> capture, the local electricity grid capacity to accept additional electricity output and the ability of the downstream transport and storage networks to handle large changes in flow rates of CO<sub>2</sub>. Further work could consider a more detailed analysis of power plant performance when bypassing the CO<sub>2</sub> capture unit and also any additional costs that might be associated with this and other operating modes (e.g. impact on maintenance schedules and component lifetime). Such analysis could also usefully explore the costs associated with start-up and shutdown (which may be increased or decreased with variable capture depending on the operating mode chosen). Multiple train capture units will change the shape of the EOP curve significantly, lower capture levels may be more energetically feasible.

Bypass and subsequent additional electricity export is dependent upon the ability of the plant to operate without capture, the local grid capacity to accept additional electricity output and the ability of the downstream transport and storage networks to handle large changes in flow rates of CO<sub>2</sub>. It is assumed in this work that that these conditions can be met.

Any other additional costs associated with a bypass, e.g. the impact of component lifetime, and ramp times for changes to capture and plant bypass are outside the remit of this work. Where full bypass of the capture plant is an option, there will be a range of carbon and electricity prices where, for a given EOP relationship, it will be financially beneficial to bypass the plant. The shift between capture and bypass occur when the net SRCF of operation with capture becomes lower than the net SRCF achieved by bypassing the capture plant

Costs associated with start-up and shutdown including increased wear as the result of increased stresses resulting from changes to capture level of the plant but would need to be included in the variable cost of CCS in order to represent the true costs of unit flexibility and comparative benefits from ramping capture levels

The analysis reported in this paper shows that the inherent volatilities in electricity value (through varying electricity demand/supply balance) and carbon emission costs also lead to continuous adjustment of capture levels being necessary to achieve cost-effective low carbon electricity supply. The results show that plants seeking to maximise their returns in the market may operate at capture levels that are significantly different from their nominal design values. This holds implications for plant design and operating strategies, differing from optimal steady state designs. Potential variations in configuration and design are, therefore, discussed and assessed.

Although quantitative analysis of these ‘whole systems’ impacts is beyond the immediate scope of this analysis some potential priorities for further work in this area are identified.

## References

- [1] Davison JE. Performance and costs of power plants with capture and storage of CO<sub>2</sub>. *Energy* 2007;32:1163-1176.
- [2] Rao, AB, Rubin AB. Identifying cost-effective CO<sub>2</sub> control levels for amine-based CO<sub>2</sub> capture systems. *Ind Eng Chem Res* 2006;45:2421–2429.
- [3] Chalmers H, Lucquiaud M, Gibbins J, Leach, M. Flexible operation of coal fired power plants with post combustion capture of carbon dioxide. *ASCE Journal of Environmental Engineering* 2009;135:449-458.
- [4] Chalmers H, Leach M, Lucquiaud M, Gibbins J. Valuing flexible operation of power plants with CO<sub>2</sub> capture. *Energy Procedia* 2009;1:4289–4296.
- [5] Hildebrand AN, Herzog HJ. Optimization of carbon capture percentage for technical and economic impact of near-term CCS implementation at coal-fired power plants. *Energy Procedia* 2009;1:4135–4142.
- [6] Cohen SM, Rochelle GT, Webber ME. Turning CO<sub>2</sub> capture on & off in response to electric grid demand: A baseline analysis of emissions and economics. *ASME Journal of Energy Resources Technology* 2010;132:8.
- [7] Cohen SM, Chalmers H, Webber ME, King CW. Comparing post-combustion CO<sub>2</sub> capture operation at retrofitted coal-fired power plants in the Texas and Great Britain electric grids. *Environmental Research Letters* 2011;6.
- [8] Cohen SM, Rochelle GT, Webber ME. Optimal operation of flexible post-combustion CO<sub>2</sub> capture in response to volatile electricity prices *Energy Procedia* 2011;4:2604–2611.
- [9] Ziaii S, Cohen SM, Rochelle GT, Edgar TF, Webber ME. Dynamic operation of amine scrubbing in response to electricity demand and pricing. *Energy Procedia* 2009;1:1047-4053.
- [10] Ziaii S, Rochelle GT, Edgar TF. Optimum design and control of amine scrubbing in response to electricity and CO<sub>2</sub> prices. *Energy Procedia* 2011;4:1683-1690.
- [11] NETL. Cost and performance of PC and IGCC plants for a range of carbon dioxide capture, Revision1. DOE/NETL 2011/1498; 2013.
- [12] Bhowan AS, Freeman BC. Analysis and status of post-combustion carbon dioxide capture technologies. *Environmental Science & Technology* 2011;45:8624-8632.
- [13] IPCC. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: 2013.
- [14] Brasington R D. Integration and operation of post-combustion capture system on coal-fired power generation: load following and peak power. Doctoral dissertation: Massachusetts Institute of Technology 2012.
- [15] Coussy P, Raynal L. CO<sub>2</sub> capture rate sensitivity versus purchase of CO<sub>2</sub> quotas. Optimizing investment choice for electricity sector. *Oil & Gas Science and Technology—Revue d'IFP Energies Nouvelles*; 2013.
- [16] Lucquiaud L, Gibbins J. Effective retrofitting of post-combustion CO<sub>2</sub> capture to coal-fired power plants and insensitivity of CO<sub>2</sub> abatement costs to base plant efficiency. *International Journal of Greenhouse Gas Control* 2011;5:427–438
- [17] Joskow PL. Comparing the costs of intermittent and dispatchable electricity generating technologies, *American Economic Review: Papers & Proceedings* 2011;100:238–241
- [18] Chalmers H. Opportunities and challenges for flexible operation of pulverised coal power plants with CO<sub>2</sub> capture. Doctoral thesis, University of Surrey 2010.