Greenhouse Gas (GHG) Emissions from Electricity Generating CCS upstream and downstream transport processes

Tim Cockerill[1*], Naser Odeh[2] & Scott Laczay[1]
[1]ICEPT, Imperial College London, UK
[2]AEA PLC (formerly at University of Reading)

* Corresponding author email: t.cockerill@imperial.ac.uk

ABSTRACT

Headline figures suggest CCS technology will capture 90% or more of the CO_2 produced by a power plant. While this may be true at the stack, on a full lifecycle basis the GHG savings offered are more modest thanks to significant resource consumption in upstream and downstream processes. Our analysis suggests lifecycle GHG emissions can be reduced to approximately 170 gCO_2/kWh for an integrated gasification combined cycle (IGCC) plant with 90% capture efficiency. This still represents around an 80% saving compared to conventional coal plant, but is considerably higher than the better performing renewables such as wind that produces only 10-30 gCO_2/kWh in good locations

This paper examines the origin and importance of upstream and downstream CCS GHG emissions, in particular identifying those associated with transport processes. Sensitivity studies investigate which major characteristics of a CCS system are likely to have an important impact on transport GHG emissions. The scope for combining biofuels with CCS in order to improve lifecycle performance is considered. In principle BioCCS could produce a system with overall negative atmospheric GHG emissions. However that potential is constrained by emissions arising from the production and transportation of biofuels.

Finally some general conclusions for design approaches for CCS systems aimed at minimising system GHG emissions are drawn. Some key areas of uncertainty are also identified for further work.

1. INTRODUCTION

Headline figures suggest CCS technology will capture 90% or more of the CO_2 produced by a power plant. While this may be true at the stack, on a full lifecycle basis the GHG savings offered are likely to be more modest thanks to significant resource consumption in upstream and downstream processes. This paper summarises results from a series of life-cycle analysis investigations of hypothetical fossil fuel based electricity generating CCS plant, emphasizing the role, albeit relatively small, that transport systems play in contributing to the overall emissions. The discussion encompasses both downstream transport systems (i.e. for carbon dioxide) and upstream systems (i.e. for fuel and consumable materials). Much of this discussion draws on analysis substantially reported in two publications by two of the authors [1], [2].

The performance of the fossil fuel based CCS systems is compared to that of several electricity generating renewable energy technologies. Subsequently the potential offered by combining biomass and CCS technologies, with the ultimate objective of producing net carbon dioxide capture, from the atmosphere is examined. The results from this section of the paper are necessarily indicative as there are many uncertainties about the GHG impacts of biomass production and combustion, let alone the complexities introduced by combining biomass combustion with carbon capture technologies. In consequence, considerable care must be exercised in quantitatively comparing the various results presented throughout the paper.

Nevertheless, the qualitative trends are clear enough to allow some useful conclusions to be drawn.

2. OVERVIEW OF THE LIFE CYCLE ANALYSIS APPROACH

Life cycle analysis (LCA) is a standardized method for evaluating the environmental impacts of a given process or different competing processes. Greenhouse gas emissions, other air and water emissions, resource consumption and energy use are evaluated using energy and material balances. The evaluation procedure covers all sub-processes within the life cycle of the system starting from raw material production and ending with product and waste disposal. By evaluating the environmental impacts of different systems, recommendations can be made to reduce possible effects. The work reported here makes use of LCA in studying the impacts (with emphasis on GHG emissions) of fossil fuel power generation with and without CCS. The main objective is to evaluate the actual reduction in GHG emissions that can be realised by CCS in various configurations.

Broadly speaking, each of the systems studied consists of fuel production, its transportation to the power plant, power plant construction, power plant operation and any processes related to power/capture plant operation. For all CCS technologies, the analysis also includes the capture plant construction and operation in addition to CO_2 transport and storage.

3. SYSTEM SPECIFICATION

3.1 System boundaries

Figure 1 summarises the extent of the system considered by the lifecycle analysis results presented here, with further detail of individual elements in Table 1. The key element of course is the power plant itself, and our calculations include direct emissions from combustion, plant internal energy consumption, energy used in operating an monoethanolamine (MEA) based capture system, and energy for plant maintenance activities. Note that the impacts of electricity transmission beyond the power station are not included, and thus the results quoted here are for electricity produced rather than delivered.

Upstream process direct emissions include those arising from fuel production activities, encompassing the energy used to operate the machinery and transport systems required. Also included within upstream processes is the production of other consumable materials such as limestone, ammonia and monoethanolamine. For gas cycle systems, leakage from pipelines is accounted for. Indirect upstream emissions take account of equipment manufacturing, recognising that production facilities are not dedicated to servicing the power plant and the associated emissions should be shared across all uses. Downstream processes consider waste transport and disposal in relatively nearby locations. As with the upstream analysis where non-dedicated facilities are used, emissions are attributed appropriately across all uses.

As the figure shows, emissions arising from the construction phases across all the supply chain elements are included in the calculations, taking account of

- Materials
- Materials production processes
- Material transportation by truck over an average distance of 50km
- Onsite energy consumption, comprising 80% diesel and 20% electricity taken from the UK grid.

Power plant decommissioning is accounted for, but decommissioning of upstream and downstream equipment is not included.

3.2 External factors

As well as the system boundary, another important influence on the assessment is the location of the plant and the resources consumed in construction and operations. The analysis in sections 4-6 of this paper has been developed on the basis that the plant is located in North-East England, and that fuel and other materials are sourced relatively locally so far as possible. Table 2 provides more comprehensive details.

4. LIFE CYCLE EMISSIONS FOR FOSSIL FUELED CCS PLANT

4.1 Power plant types

Four types of fossil fuel plant are considered here as follows:

- A supercritical pulverized (SuperPC) coal fired plant with selective catalytic reduction (SCR), electrostatic precipitation (ESP) and flue gas desulpherisation (FGD) pipe-end clean up technologies
- A similar supercritical coal fired plant, but fitted additionally with a monoethanolamine (MEA) based CO_2 capture unit having 90% CO_2 capture efficiency
- A natural gas fired combined cycle (NGCC) plant fitted with similar MEA based capture unit
- A coal fired integrated gasification combined cycle (IGCC) plant fitted with Selexol based carbon dioxide capture, again having 90% capture efficiency

The calculations assume that plant have a rated capacity of 500 MWe, an operating lifetime of 30 years and take 3 years to build. Load factors are taken as 75% except in the first and last year of operation where factors of only 37.5% are achieved due to commissioning and decommissioning activities respectively. Further outline details of the power plant are contained in Table 3 to Table 6, but for full information reference should be made to the authors previous work [1],[2].

4.2 Overall results

A breakdown of the results is shown in Figure 2 and Table 7. Unsurprisingly the supercritical plant without CCS produces by far the largest atmospheric GHG emissions per unit of electricity output, dominated by the direct emissions from combustion. All the CCS fitted plant produce considerably less atmospheric emissions, with the coal fired IGGC plant generating the smallest quantity of emissions per unit (kWh) of electricity produced.

4.3 Emissions associated with transport processes

4.3.1 Downstream

In all the CCS cases, emissions associated with CO_2 transport are very small, representing between 1% and 1.8% of the total per unit of electricity prroduced. This of course only applies for the system specification set out in section 3. The component of these emissions arising from powering any recompression stations could change if energy sources with differing carbon intensities were employed – the present study has assumed they are powered by electricity generated with the GB grid average carbon intensity.

With longer or less secure pipelines the impact of CO_2 transport could increase considerably, as investigated in section 4.3.3. Other downstream processes include ash and other solid waste disposal. These also make only a very small contribution to overall emissions.

4.3.2 Upstream

Upstream emissions are included within the "operation" components of Figure 2, which also includes the very small downstream operational emissions associates with ash and waste disposal. The upstream calculations assume coal is produced from a nearby UK deep mine and subsequently transported to the power plant by rail. This represents something of an idealised best case, as the limited number of UK mines means transport will in general be over longer distances. Limestone is also UK sourced and transported by truck, with other consumables such as solvents transported by rail. Natural gas is assumed to be sourced from the UK North Sea, carried via pipelines with the specification set out in Table 9.

For the base coal CCS configurations considered here, in general just less than 50% of upstream emissions arises from mining, with a similar contribution coming from the production and transport of all other consumables. Coal transport accounts for approximately 1.5% of upstream emissions, though as will be seen later, this low value is largely a reflection of very optimistic assumptions.

For the natural gas CCS system considered the majority of the calculated upstream GHG emissions arise because of escapes in the natural gas supply system, though it should be noted that we have assumed comparatively high leakage rate of 1%. Smaller contributions are distributed over the production and transport of other consumables.

Across all the results for CCS plant it is clear that the operational GHG emissions are much large than those from CO_2 transport. Indeed under the assumptions set out here, emissions from pipeline CO_2 transport are almost negligible compared to direct emissions, operational emissions and emissions associated with capture. In the carbon capture transport and storage (CCTS) system, the transport element appears to have a tiny impact on GHG emissions.

4.3.3 Sensitivity study

Figure 3 illustrates how sensitive GHG emissions from each of the CCS plant are to system changes, with an emphasis on transport processes. It is immediately clear the details of the CO_2 transport system have relatively little effect, as increasing the pipeline network length by 100 km raises lifecycle emissions by between 0.05% (PC+CCS) and 0.08% (IGCC+CCS). The details of the other downstream processes, and in particular plant ash waste disposal, also seem unimportant.

Upstream transport processes are much more important. Importing coal from Russia, rather than relying on local production, has a severe influence on the emissions for the PC and IGCC plant. Much of this is due to emissions from the transportation processes, though it has also been assumed here that a poorer quality coal is delivered. Similarly, supplying the NGCC+CCS plant from a gas network with two percentage points greater leakage increases lifecycle GHG emissions by about one-third.

Also of great importance is the effectiveness of CO_2 capture. A 5% reduction in the overall proportion of CO_2 captured unsurprisingly gives a substantial increase in GHG emissions in all cases. This result remains qualitatively true irrespective of whether the reduction is due to less effective capture equipment, or increased leakage from a pipeline transport system.

The key conclusion is that in terms of GHG emissions of a CCS system, most of the details of the downstream processes are relatively unimportant. This presents a stark contrast to upstream transport processes, which our results suggest have a much larger impact on emissions. If a design objective is to minimize lifecycle emissions, CCS systems should in general be situated to promote ease and effectiveness of fuel supply, and with little regard to the implications for the CO_2 pipeline transport network. However, one important factor impacting the lifecycle performance is the total CO_2 captured, and the downstream transport system has the potential to influence this with respect to its resistance to leaks. While the overall configuration of the CO_2 transport system has little impact on GHG emissions, it is vitally important that transport is as secure as possible.

5. COMPARISON WITH OTHER LOW CARBON ENERGY SOURCES

For comparison purposes, Table 8 shows ranges of values for GHG emissions from other low-carbon electricity production systems taken from the literature. In general it is clear that, despite producing much lower carbon emissions than conventional fossil fueled plant, CCS cannot produce electricity that is as low carbon as most renewables.

It should be noted though that the dividing line is rather fuzzy and dependent on the location and system boundary of the renewable energy technology. Solar PV in locations with poor resources can result in emissions per kWh higher than those calculated here for IGCC systems. Equally most of the renewable energy systems assessments do not take account of the impact of intermittency on the lifecycle emissions. Including electricity storage facilities within the system boundary, for example, can dramatically worsen the environmental performance. This raises a number of complex issues that are beyond the scope of this paper, but it should be kept in mind that fossil fuel based CCS systems have the potential to offer supply controllability and a geographical independence that certain renewables find difficult to match without additional facilities.

One possible way of further reducing the emissions of CCS systems is by combining them with biomass fuels. The potential of this technology is considered in the remainder of this paper.

6. LIFECYCLE ANALYSIS OF BIO-CCS

6.1 Objectives

CCS with biofuel firing (BioCCS) offers the attractive potential of producing a net removal of carbon dioxide from the atmosphere, since the carbon dioxide released by biomass combustion was originally absorbed from the atmosphere in photosynthesis. A further high-level study has examined the lifecycle implications of BioCCS drawing on the outputs of the UKCCSC supported study, supplemented with data from the literature as described in detail by Laczay [3]. Both pure-biofuel and coal co-firing cases have been examined with the pure-biofuel cases considering both miscanthus and RC willow as fuels. For the co-firing case, only miscanthus was analysed.

6.2 Approach and assumptions

The study considers a circulating fluidized bed (CFB) power plant comparable to the 550 MWth / 240 MWe facility operated by Alholmens Kraft in Pietarssaari, Finland [4]. This plant operates at a typical thermal efficiency of 38%, but it was assumed that a 90% effective CO_2

capture system would reduce the power output by 25%, giving an overall conversion efficiency for the BioCCS system of 28.5%.

Due to the complexities associated with biomass lifecycle analysis, this work used a simplified approach. In particular, emissions associated with power plant and CO_2 pipeline construction processes have been neglected. As the latter are relatively small this assumption is unlikely to have a significant influence on the results. The former are more likely to have an impact on the detail of the calculations, but not the qualitative conclusions. Emissions associated with the up-keep of the carbon capture system, for example solvent replacement, have also been neglected.

It should also be kept in mind that the study takes no account of the whole system indirect impacts of wider biomass use, such as induced land use change (ILUC), which, it is argued, could have a devastating effect on the lifecycle sustainability of certain biofuels. There has been much recent debate about the GHG emissions that should be associated with biofuel production, typified by the Searching-Wang debate (see for example [5]) with the Gallagher Review providing an excellent reference [6]. The calculations reported here account for only the emissions that arise directly from biomass cultivation, processing and harvesting operations.

The Biomass Environmental Assessment Tool (BEAT2) [7, 8] was used to calculate the energy yield and combustion products in all cases, with the following parameters:

- All power plant operate with an annual load factor of 90%
- For ***miscanthus*** yields are 18 wet tonnes per hectare per year, having 30% moisture content. Once harvested the feedstock is naturally dried in storage for 40 days reducing the moisture content to 10%. 60 kg of Nitrogen fertilizer is used when establishing each hectare, and a production cycle lasts 15 years after which the plantation must be cleared and re-established.
- For ***willow*** yields are 14 wet tones with 50% moisture content, with the feedstock dried to 10% moisture content
- Energy crops are transported by truck 100 km from the plantation to the storage/processing site, with a further 100 km journey to the power plant.
- Losses of 7% occur, 11% during storage and 3% during transport of energy crops
- Coal is imported from South America, USA, Australia and South Africa

6.2 Results

Table 10 shows the calculated lifecycle GHG emissions for the pure-biomass based CFB power plant with CCS. Both cases show strongly negative net GHG emissions, with the 90% capture rate more than compensating for the emissions that do reach the atmosphere. The net emissions are sufficiently negative that the simplifications outlined earlier are very unlikely to change the qualitative conclusion

More detail is shown in Figure 6, which compares the origins of the emissions reaching the atmosphere. The upstream processes for miscanthus and SRC willow show slight differences in emissions. Miscanthus has more emissions associated with cultivation/harvest compared to willow. This is due to differences in the planting and harvesting processes of the two energy crops. Miscanthus also has much higher transport emissions than SRC willow because it is bailed rather than chipped. Chips are more densely transported, and as a result, miscanthus transport emissions are nearly twice that of chipped SRC willow.

Results for co-firing with coal are shown in Figure 7, where the vertical axis represents net atmospheric GHG emissions per kWh of electricity produced relative to a supercritical coal power plant without a CO2 capture unit. Unsurprisingly, net emissions reduce almost in direct proportion to the proportion by energy value of biomass in the fuel mix. A useful observation is that miscanthus based BioCCS appears to become GHG neutral for a co-firing level of approximately 20%. Higher proportions of biomass produce net capture from the atmosphere, though some care is necessary in interpreting the values in the light of the simplifications outlined earlier

7. DISCUSSION

7.1 Emission minimization strategies

Presumably a key objective in the design of any electricity producing CCS system is to generate power with the lowest achievable GHG emissions per unit. To reach this objective, the results in this paper suggest that there is some value in adopting an integrated approach to the design of the whole system as decisions made in one part of the CCTS chain can have implications for the GHG emission of another. Minimising overall emissions requires that such interactions are fully accounted for.

In the cases considered here, downstream pipeline based CO_2 transport does not have a substantial influence on overall GHG emissions, and thus can largely be designed independently from the rest of the system in this regard. Pipeline CO_2 transport can influence system GHG emissions via leakage, and hence minimising escapes should be a primary design objective.

For countries of scales similar to the UK, pipeline length does not have a significant effect on overall GHG emissions. Hence the CO_2 transport distance should not play major role in CCS plant site selection. Upstream transport processes, notably fuel transport, have a much stronger impact on emissions and should have an influence on site selection. Clearly any whole-system GHG minimisation strategy should focus on simplifying fuel rather than CO_2 processing and transport, so long as any risk of CO_2 leakage is avoided. This is particularly true with biomass based CCS systems.

7.2 Areas of uncertainty

While undertaking this work we have identified a number of areas where limited technical understanding constrains the usefulness of LCA approaches for the analysis and optimization of future CCS systems. The two most important, in the opinion of the author, are discussed in this section.

7.2.1 Operational effects

Most LCA analyses assume that the systems they study operate under steady state, full-load conditions, and this is true of almost all CCS studies. Where some account is taken of variable loading, typically, analysts use only a load factor approach to account for periods of non-generation. Where plant will be used predominantly to supply base-load, this is a reasonable assumption, especially as construction makes a relatively small contribution to overall emissions even for CCS power plant

The vagaries of the electricity market mean that base-load operation is unlikely for all CCS systems in practice. As a result, some plant might be subject to substantial numbers of cold-start and shut down procedures, as operators try to optimize their financial return. Operators may also wish to run plant at part load. From a lifecycle GHG emissions perspective non-steady state and part load operations are likely to exhibit much poorer efficiency than state-state full load operation. In consequence they have the potential to substantially increase the overall GHG emissions of a CCS system, particularly if they are frequent events.

New CCS plant will most likely be initially conceived for base-load operation, and thus it could be argued that their lifecycle performance will not be impacted by non-steady state operation. Over their lifetime though there will be substantial changes in energy and electricity markets, and as they age, CCS plant are likely be moved towards a peaking role as is common with existing old fossil fuel plant [9]. Moreover, expected increasing penetration of intermittent renewables will push even CCS fossil plant towards operating regimes that are more variable than those experienced by existing fossil plant.

Evaluating the impact of transient operation on GHG performance is hindered by poor understanding of both CCS plant and carbon dioxide transport systems under such conditions. Further work is required in these areas in order to fully evaluate 'real world' performance of future CCS systems.

7.2.2 Impact of biomass combustion products on CCS efficiency

While the results in this paper suggest that biomass to power combined with CCS has the potential to produce negative lifecycle GHG emissions, it is important to keep in mind that the underlying calculations assumed there was no detrimental interaction between the biomass combustion products and both the capture system together with the CO_2 transport system. In general this would seem a reasonable assumption, it being widely accepted that co-firing reduces the emission of pollutant elements (including sulphur, nitrogen and mercury) in comparison to pure coal. However biomass co-firing can yield increased concentration of hydrochloric acid in flue gases [10].

Again there is scant data available in the literature regarding the effect of biomass combustion products on CO_2 capture and transport processes. Further technical data is required before the LCA can be taken forward.

8. CONCLUSIONS

Transport emissions are a relatively small component of the GHG emissions from CCS systems, though the quantities vary considerably with the assumptions underlying the lifecycle analysis. As a general rule, downstream emissions associated with pipeline CO_2 transport are almost negligible, certainly with respect to the construction of short pipelines. Operational emissions depend on the source of the energy used to power recompressions stations. However any CO_2 leakage from the pipeline system to the atmosphere has the potential to dramatically increase the impact of downstream transport processes.

Upstream transport emissions, predominantly for fuel, are more important, typically representing at least 2% of all GHG emissions. For biofuels, upstream emissions are considerably more important. This is true even without taking account of the current uncertainty surrounding the whole system sustainability of biofuels, as typified by the Searchinger-Wang debate.

The results have implications for reducing lifecycle GHG emissions from CCS plant by optimizing plant location. In particular, the lifecycle GHG impacts are much more sensitive to fuel transport processes than downstream carbon dioxide transport. From the GHG perspective, it is suggested that optimal plant location strategies for the UK should focus on minimizing fuel processing and transport, and not be overly concerned about CO_2 transportation distance. This is especially true for biomass derived fuels, even if they are sourced from the UK.

There are two key areas of uncertainty that have had relatively scant coverage in the literature and require further work. Firstly most lifecycle studies of CCS systems make substantial simplifications with respect to the operational regime of the plants under consideration. Secondly the impact that combustion of biomass fuels might have on the performance of carbon dioxide capture systems does not appear to have been extensively considered in LCA studies of CCS systems. Such an extension can be readily included within the lifecycle methodology in principle, but there is a scarcity of data to support such work.

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Category	**Coal-based systems**	**Natural gas-based systems**
Construction	- Power plant construction - Capture plant construction - CO_2 transport pipeline	- Power plant - Gas pipeline - Capture plant - CO_2 transport pipeline
Fuel combustion	Direct CO_2 emissions	Direct CO_2 emissions
Fuel production	Mining (Equipment manufacture, Mining activities, Methane leakage, Coal cleaning, Land recovery for surface mining)	Gas extraction (platform construction, gas sweetening and flaring, methane leakage)
Other material production	- Limestone/ammonia production - SCR catalyst production - Water treatment and distribution - MEA production - NaOH/activated C production	- Ammonia production - SCR catalyst production - Water treatment and distribution - MEA production - NaOH/activated C production
Waste disposal	- Boiler/ESP/Gasifier ash - FGD waste - SCR catalyst waste - MEA re-claimer waste	- SCR catalyst waste - MEA re-claimer waste

Transport	- Coal transport
	  - Local by rail
	  - International by ship
	- Limestone transport by truck
	- Chemical transport by rail
	- Waste transport by truck
	- CO_2 compression and injection
		- Gas transport
		  - gas compression
		  - onshore processing
		  - Methane leakage
		- Chemical transport by rail
		- Waste transport by truck
		- CO_2 compression and injection

Table 1: Details of the sub-processes included within the lifecycle analysis of sections 3 and 4.

Category	**Coal-based power plants**	**Gas-based power plants**
Power Plant Location	Teesside	
Mine location	Surface mine: Maiden's Hall Extension, Northumberland Deep mine: Killingley Colliery, North Yorkshire	- -
Limestone Quarry	North Yorkshire: 50 km from power plant	-
Ammonia production	Billingham, Durham, 20 km from power plant	
Concrete manufacturer	Leeds, 100 km from power plant	
Steel manufacturers	Teesside	
Gas field	-	Southern North Sea
On-shore gas processing	-	Hartlepool
Gas pipeline	-	Offshore: 100 km, on-shore: 50 km
CO_2 on-shore collection point	Teesside within 50 km from power plant	
CO_2 pipeline	50 km on-shore, 150 km offshore	
CO_2 storage	Bunter Sandstone-Southern North Sea, Closure	

Table 2: Location of power plant and key material inputs.

Parameter	Value
Ambient temperature, ºC	15
Ambient pressure, kPa	101
Steam cycle heating rate, MJ/kWh	7.4
Excess air, %	20
Temperature of flue gas exiting boiler, ºC	370
Load factor, %	75
Life time, years	30
ID fan efficiency, %	85

Table 3: Key parameters for the Supercritical PC Plant

Parameter	Value
Number of gas turbines	2
Excess air, %	180
NOx emissions rate, ppm	10
Air compressor ratio	15.7
Compressor efficiency, %	70
Pressure loss across combustor, kPa	28
Temperature into turbine, ºC	1330
Turbine isentropic efficiency, %	85
Mechanical and generator efficiencies, %	98

Table 4: Key parameters for the NGCC plant

Parameter	Value
Type of gasifier	GE oxygen-blown
Gasifier temperature, ºC	1250
Gasifier pressure, MPa	6
Steam input to gasifier, mol H_2O / mol C	0.45
Carbon loss, %	1
Oxidant pressure (at outlet of ASU), MPa	4
Oxidant composition, %O_2 : % Ar : % N_2	95 : 4: 1
Particulate removal efficiency from syngas, %	50
COS to H_2S conversion efficiency, %	98
H_2S removal efficiency, %	98
COS removal efficiency, %	40
CO to CO_2 conversion efficiency, %	95
Sulphur recovery efficiency, %	95
Steam added to shift reactor, mol H_2O/ mol CO converted	1

Table 5: Key parameters for the IGCC plant with Selexol capture

Parameter	Value
CO_2 removal efficiency, %	90
SO_2 removal efficiency in capture plant, %	99
SO_2 removal efficiency in FGD, %	98
SO_3 removal efficiency in capture plant, %	99
HCl removal efficiency in FGD, %	95
NO_2 removal efficiency in capture plant, %	25
Ash removal efficiency in FGD, %	50
MEA concentration, %w/w	30
Lean CO_2 loading, mol CO_2/mol MEA	0.2
Blower efficiency, %	75
Pressure across blower, kPa	15
Sorbent pump efficiency, %	75
Pressure across pump, kPa	200
Compressor efficiency, %	80
CO_2 outlet pressure, MPa	13.5

Table 6: Key parameters for MEA-based capture process.

Plant Type	Source of GHG Emissions (gCO2e/kWh)					Total Emissions
	Construction	***Direct***	***Operation***	***CO2 Capture***	***CO2 Transport***	
Super-Crit Coal	2	788	91	0	0	881
S-C Coal + CCS	3	107	124	22	3	258
NGCC + CCS	3	42	118	25	2	190
IGCC + CCS	3	90	73	1	3	170

Table 7: Summary of Lifecycle GHG for representative power plant.

Technology	Range of GHG emissions (gCO_2/kWh)	References	Comments
Hydro	3-33	[11], [12], [13], [14]	
Geothermal	15-23	[13], [14]	
Solar PV	39-217	[15], [14], [16], [17], [18]	Highly location dependent. Some higher values included battery storage
Solar thermal (to electricity)	30-120	[19]	Parabolic trough, centralized receiver & parabolic dish
Wind	9.7-29.5	[20],[14]	Higher values generally for offshore
Wind with pumped hydro storage	20	[21]	
Wind with compressed air storage	109	[21]	
Nuclear fission	6-24.2	[12], [22], [14]	

Table 8: Representative values for GHG emissions from several low-carbon electricity production technologies. Note that the large ranges arise partially from incompatible assumptions between the studies considered.

Diameter, cm		Thickness, mm	
On-shore	Off-shore	On-shore	Off-shore
75	100	7.8	9

Table 9: Diameter and wall thickness for natural gas pipeline.

Fuel	Miscanthus	Willow
Upstream Process GHG Emissions (A)	**73**	**57**
CO_2 from biomass combustion	*1291*	*1449*
Combustion CO_2 captured	*1162*	*1304*
Combustion CO_2 to atmosphere (B)	*129*	*145*
Net combustion CO_2 emissions (C)	**-1162**	**-1304**
Other power plant GHG emissions (D)	**19**	**15**
Direct emissions to atmosphere (A+B+D)	221	217
NET GHG EMISSIONS (A+C+D)	**-1070**	**-1232**

Table 10: Indicative life cycle GHG emissions for CFB biofuel to electricity plant with a 90% capture efficiency carbon dioxide capture plant, operating on two fuels. The overall conversion efficiency to electricity is taken to be 28.5%. All emissions are stated in $gCO_2e/kWh(e)$.

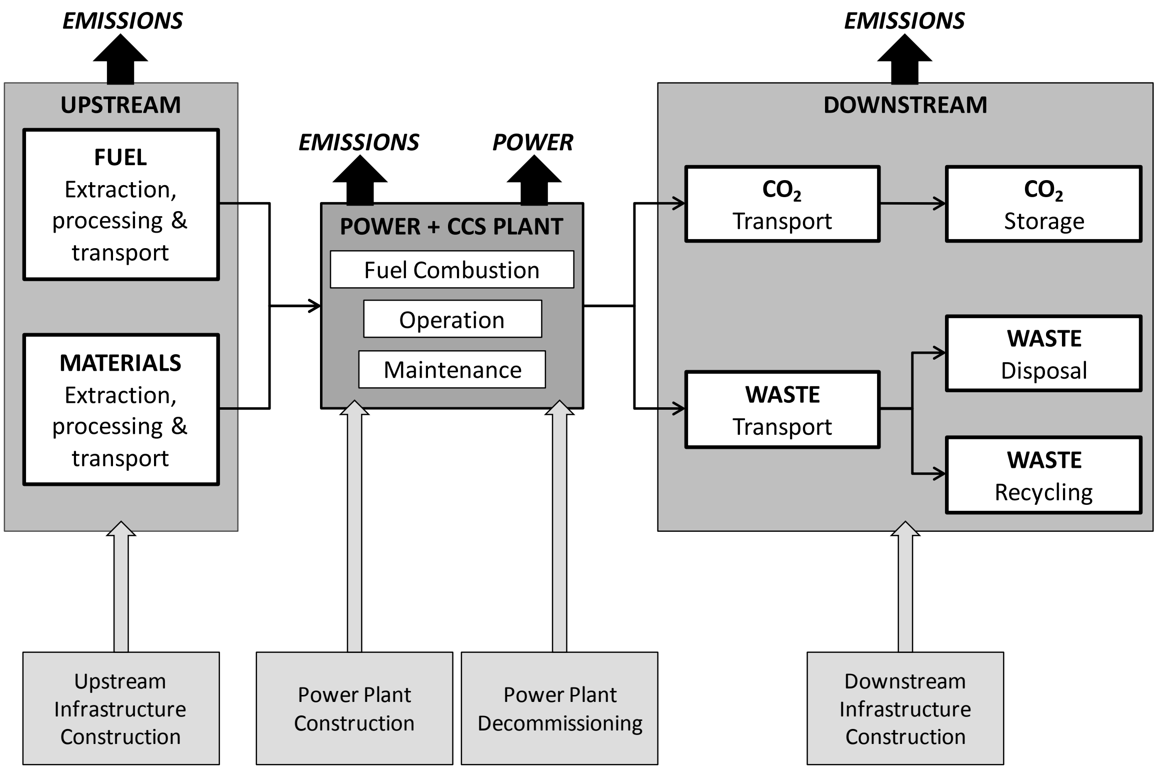

Figure 1: Summary of system boundaries for lifecycle analysis.

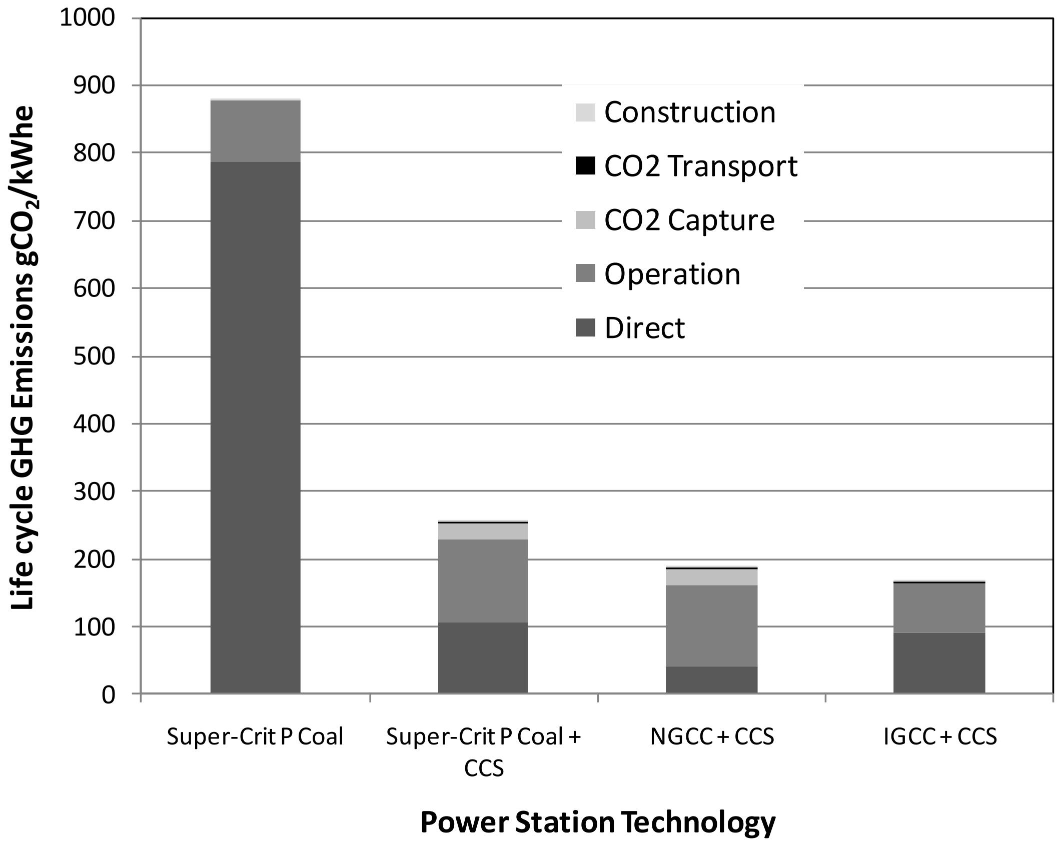

Figure 2: Breakdown of Lifecycle GHG atmospheric emissions from power plant technologies.

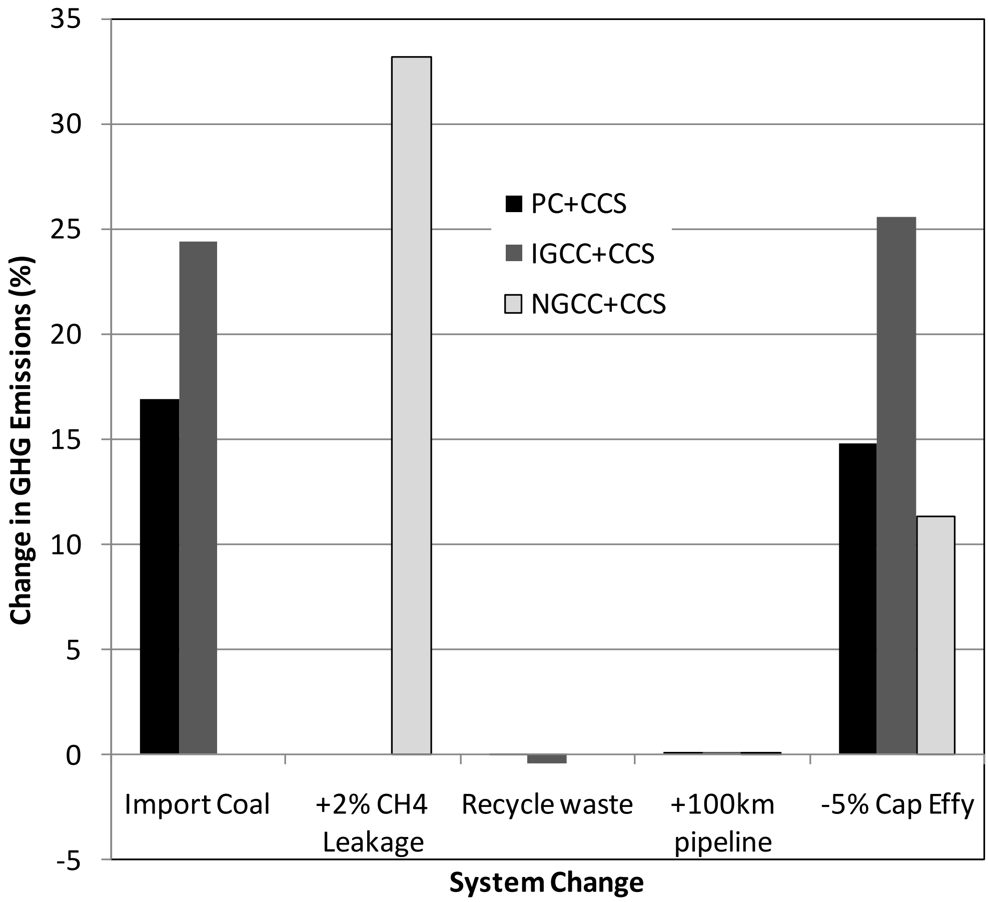

Figure 3: Sensitivity of CCS Power Plant Life Cycle GHG Emissions to System Changes. The first columns show the percentage increase in emissions for PC+CCS and IGCC+CCS plant if all coal Is imported from Russia, rather than locally sourced. The second column shows the impact for NGCC+CCS plant if methane leakage from the supply network increases by two percentage points. The third column represents the impact of recycling 50% of ash and FGD waste as construction materials. The fourth column illustrates the result of lengthening the CO_2 transmission network by 100km. The final column shows the effect of decreasing the CCS capture efficiency by 5% (assuming all other plant parameters remain the same).

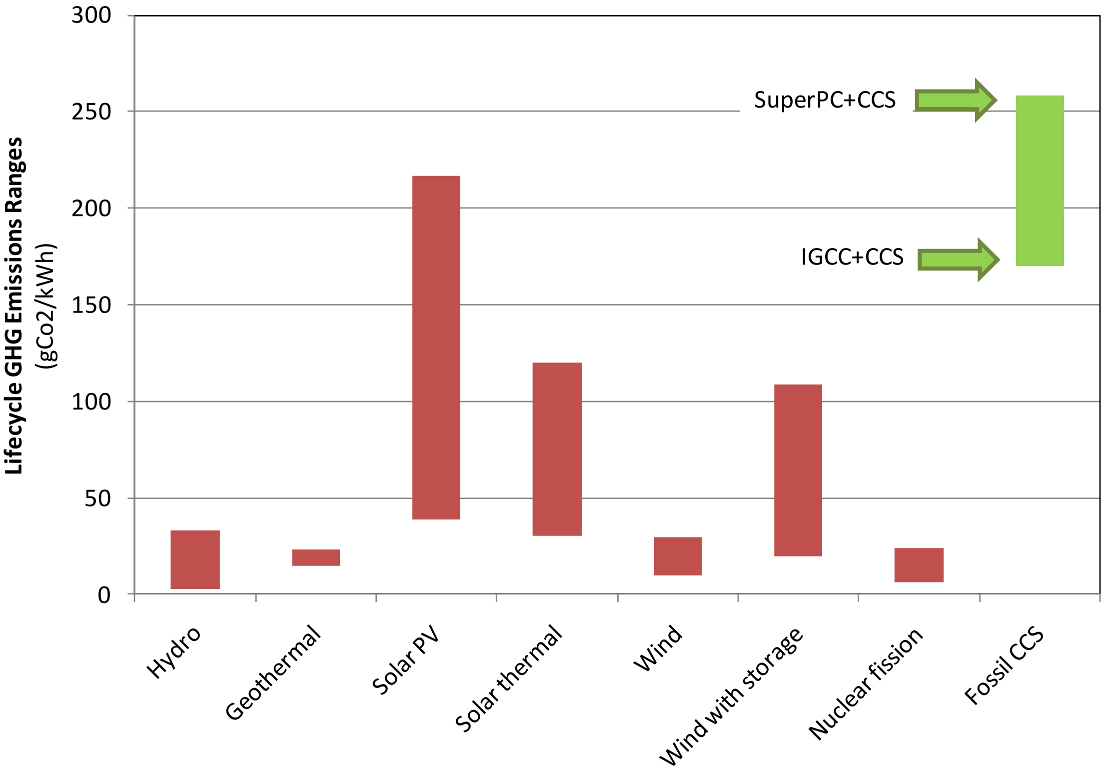

Figure 4: Lifecycle comparison of fossil CCS plant with other low carbon energy systems.

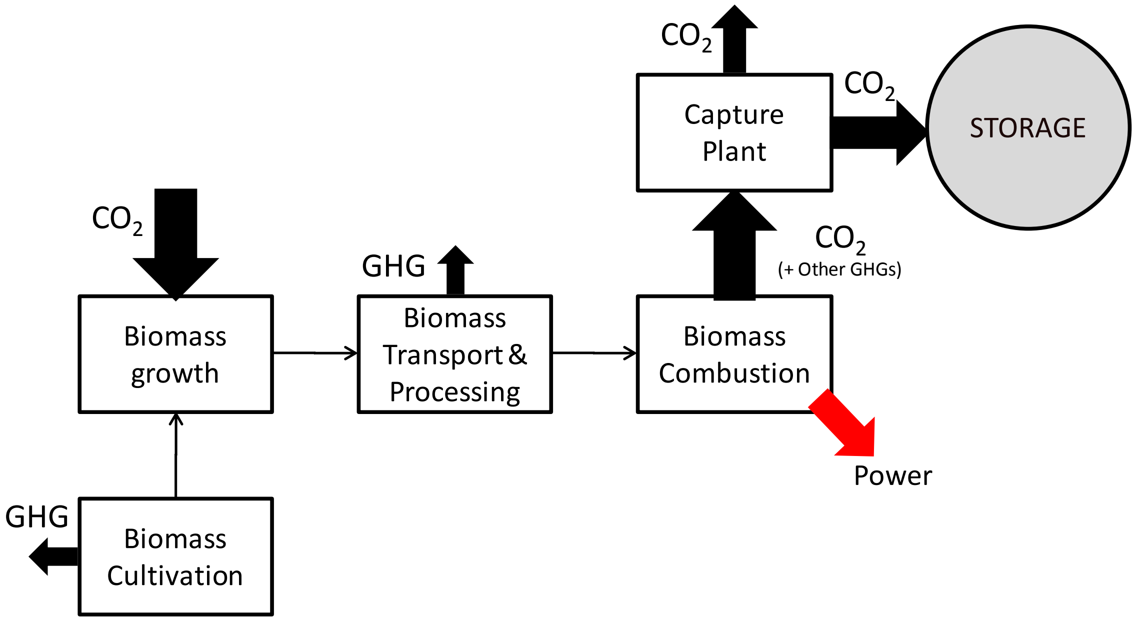

Figure 5: Biomass with CCS system summary.

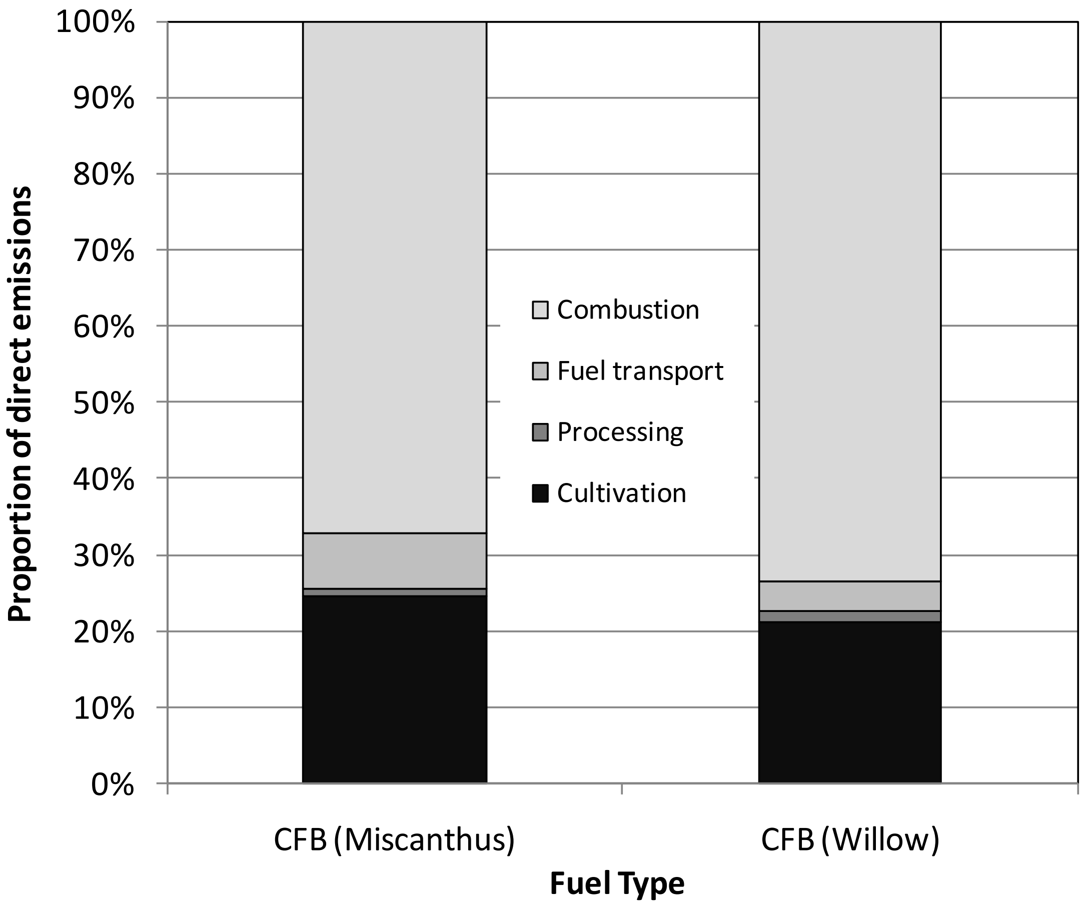

Figure 6: Breakdown of contributions to direct GHG atmospheric emissions (i.e. A+B+D in Table 10) for the Biomass with CCS system described in the text, operating on two fuels

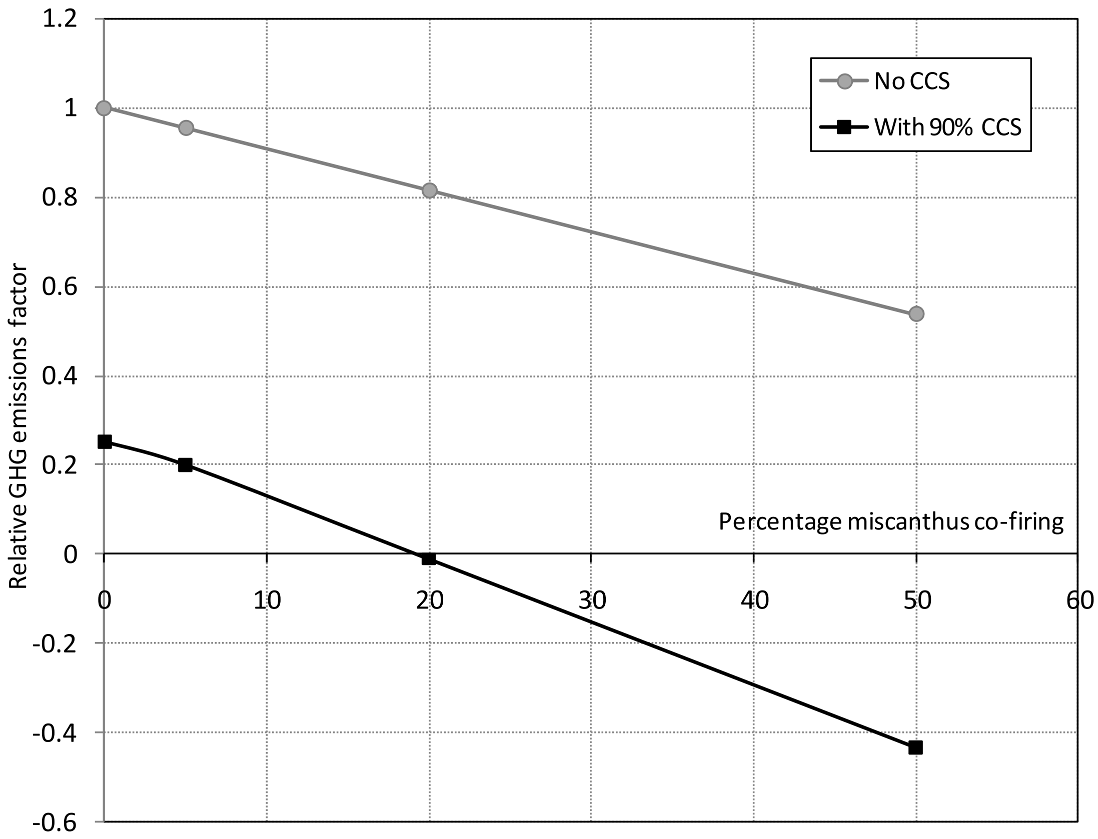

Figure 7: Relative impact of increasing levels of co-firing with miscanthus on lifecycle GHG emissions for a supercritical coal plant, with an without a carbon dioxide capture unit with a 90% capture efficiency. The vertical axis shows the emissions compared to a representative coal super-critical plant without CCS.