CLIMATE CHANGE MITIGATION BY BIOMASS GASIFICATION COMBINED WITH CO_2 CAPTURE AND STORAGE

H Audus[*], P Freund
IEA Greenhouse Gas R&D Programme, Cheltenham, U.K.

ABSTRACT

Purpose-grown, or waste, biomass products can be used to generate electricity with only a low net emission of CO_2. This is because the carbon is 'recycled' via the atmosphere. Previous work by IEAGHG, on a purpose-grown wood crop, showed that the cost of mitigation could be reduced, approaching that of fossil fuel plant with CO_2 capture and storage, by combining biomass gasification with gas turbine combustion in an integrated cycle (BIGCC).

Gasification technology combined with CO_2 capture is being seriously considered in several countries for reducing CO_2 emissions from power generation. It could also be applied to power generation from biomass; the net result would be to generate electricity with a net "negative emission" of CO_2. In this paper, the potential effectiveness of this approach is assessed in terms of cost, quantity of emissions avoided, and feasibility. Purpose-grown and by-product biomass feeds are considered.

The conclusion is that, despite the negative emissions of CO_2, biomass gasification combined with CO_2 capture and storage is likely to be less attractive than more established fossil fuel and biomass-based mitigation options. BIGCC combined with CO_2 capture and storage is not a cheap option. This applies to both the cost of electricity generated, and the cost per tonne of CO_2 emission avoided. It is more expensive than a coal IGCC with CO_2 capture, and more expensive than biomass use in BIGCC without CO_2 capture. The extent of technology development required is significant, e.g. to clean raw synthesis gas sufficiently to use in a shift-conversion catalyst, but it is possible that the technology could be used in a country that had a highly developed biomass energy industry and cheap biomass feedstock.

INTRODUCTION

In this paper, we consider the application of CO_2 capture and permanent storage to the production of electricity by biomass gasification. Several authors, e.g. Obersteiner et al. [1], have reported that combining CO_2 capture and permanent storage with biomass conversion to energy would result in the net removal of CO_2 from the atmosphere. Figure 1 illustrates the concept. Atmospheric CO_2 is adsorbed by growing biomass which is then used to produce electricity. If the CO_2 produced is returned to atmosphere, the process is essentially carbon-neutral (typical emission factors for biomass energy schemes are in the range 10-20 gCO_2/kWh; c.f. about 800 gCO_2/kWh for a modern coal-fired power station). However, if the CO_2 produced by burning biomass is captured and permanently stored, e.g. in an underground geological formation, the overall process would result in a net removal of CO_2 from the atmosphere.

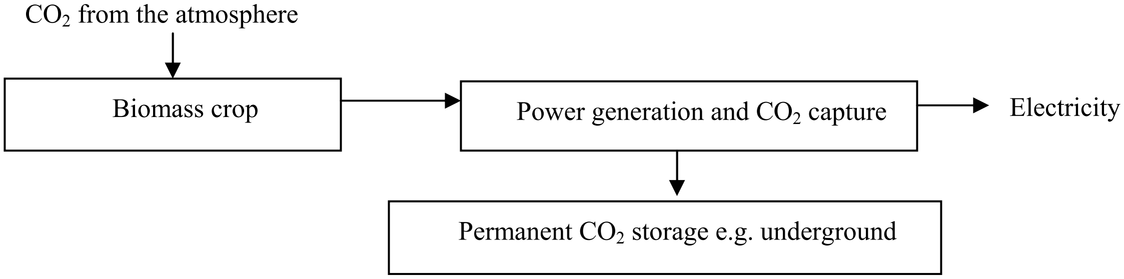

Figure 1: Power generation from biomass combined with CO_2 capture and storage

We assess potential CO_2 reduction for a processing scheme based on the production of electricity from short-rotation woody crops (SRC) grown in a sustainable manner. The SRC is converted into electricity in an integrated gasification combined cycle. Such BIGCC schemes have been assessed previously by IEAGHG, and reported to be feasible, although not yet widely used, and a relatively expensive way to produce electricity [2]. Building on the previous work, we report on the emissions, technology, and cost implications if the process is altered to include the addition of CO_2 capture and permanent storage. All costs are presented in US$; they have not been escalated from the reference figures.

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[*] Corresponding author: Email: aubeenvironment@hotmail.com

The application of BIGCC combined with CO_2 capture and storage is considered in 3 potential contexts:

- A 'Stand-alone' development in which the source of fuel, power plant, and CO_2 store are all local and not integrated into larger schemes. Land suitable for energy crops is located near a potential CO_2 store. Sufficient such developments are assumed to have taken place that the technology is commercially mature. Water is available, and a convenient connection can be made locally into the electricity grid, but there is no other opportunity for integration with CO_2 emission reduction schemes.
- A 'CO_2 intensive' development which is one of many CO_2 capture and storage schemes, some of which are fossil fuel based and much larger than the BIGCC plant. It is assumed that CO_2 transportation and storage facilities can be shared with others. Hence, the store can be large and need not be near the power plant and biomass source.
- One of many biomass developments in a 'Resource-rich' country with a growing energy demand. Development of a large-scale biomass infrastructure is a major objective. Sufficient biomass is available to meet local heat demands and to provide a surplus which could be used for production of transport fuels, hydrogen, etc. In this context the ability to produce a net reduction in CO_2 emissions whilst increasing electricity production may have commercial value. For example, if the reduction in emissions can be traded for carbon credits.

The initial focus of the paper is on the use of a purpose-grown biomass crop in the 'Stand-alone' context. This enables the costs and benefits of combining BIGCC and CO_2 capture and storage to be presented on a clear basis. We then consider how these costs and benefits would be modified by introducing the BIGCC with CO_2 capture and storage into the 'CO_2 intensive' and 'resource-rich' contexts.

We also consider use of biomass by-products i.e. the source of fuel is a residue from a commercial activity. Use of a by-product may be advantageous (as discussed later) but is an approach that complicates assessment. For example, the application is likely to be a retrofit on the primary process, and alternative uses for the by-product need to be considered which have an impact on the overall process energy balance and costs. However, it is noted that others, e.g. Möllersten et al. [3] have based evaluations of BIGCC combined with CO_2 capture and storage on the straightforward use of a biomass by-product.

GASIFICATION OF SHORT-ROTATION WOODY CROPS (SRC)

Simple biomass gasification applications are becoming commercial where a reliable feedstock is available. However, BIGCC is only at the demonstration stage. For example, in the ($6MW_e$) Sydkraft plant at Värnamo, Sweden, and the ($10MW_e$) ARBRE plant in Yorkshire, England. At the time of writing the ARBRE plant had been out of operation since July 2002 [4]. Various technical and commercial difficulties have been cited.

Size of power plant

A view needs to be taken on the size of future commercially mature BIGCC installations. In particular, how big they should be made to optimise potential scale advantages. In the IEAGHG work reported previously [2] CIEMAT (Centro de Investigaciones Energéticas, Medioambientales, y Tecnológicos, Madrid, Spain) evaluated infrastructure requirements such as land availability, accessibility to water, roads, distance to the electricity grid etc., and derived optimum power plant sizes for 28 favoured potential sites in Spain. The average plant was rated at $36MW_e$. The 30 MW_e plant used as the basis for comparisons in this paper produces electricity at the lower cost of the 2 BIGCC installations considered in detail. Figure 2 illustrates the process and gives key input and output figures.

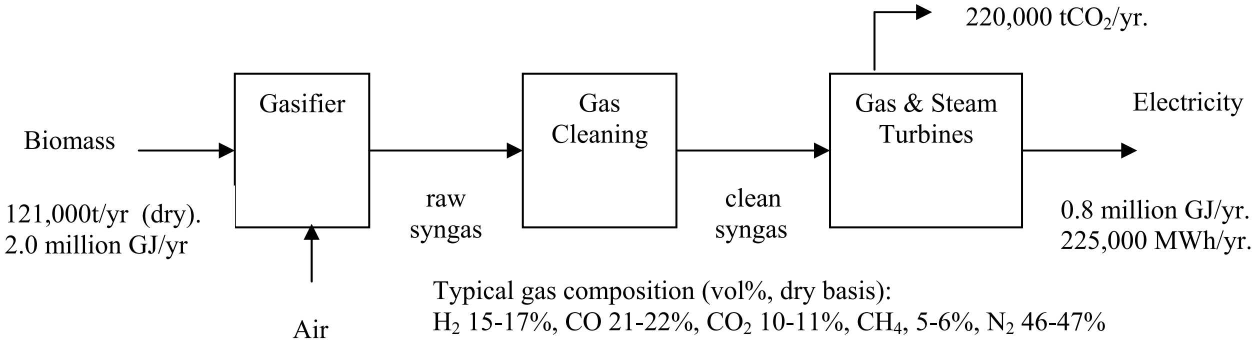


Figure 2: Biomass integrated combined cycle (without CO_2 capture)

Gas cleaning

A gas-cleaning step is required before raw syngas can be used in an efficient gas turbine. As discussed by Maniatis [5], the successful development of gas-cleaning is now recognised as a key requirement for BIGCC technology. Raw syngas can contain many contaminants, see Table 1[6]; the extent of treatment required depends on its use. Low levels of all contaminants must be achieved to avoid fouling and corrosion problems in gas turbines.

TABLE 1: RAW SYNGAS CONTAMINANTS

Contaminant	Nature	Problem
Particulate matter	ash, char, any fluid bed material	Erosion, deposition
Alkali metals	Na and K compounds	Corrosion, catalyst poison
Nitrogenous compounds	NH_3, HCN	Emissions
Tars	Polyaromatic and oxygenated hydrocarbons	Deposition, fouling, handling, and disposal problems
Sulphur and Chlorine	HCl, H_2S	Corrosion, catalyst poisoning

Generation efficiency

The optimum efficiency of a future BIGCC is a matter of conjecture. Biomass is more reactive than fossil fuels, but its energy density is lower. The degree of power cycle integration economically justifiable at a relatively small scale is likely to be low. Maniatis reports that the generating efficiency of the ARBRE BIGCC plant is 30.6% [5] and Ciferno and Marano report the Värnamo plant has an efficiency of 33%[6]. We assumed a future efficiency of 40% (LHV) for the purpose of our previous evaluation [2] and have used it in this paper also. It is within the 37-43% range of efficiencies for coal IGCC (without CO_2 capture) that was derived in recent detailed evaluation work by Bressan et al. [7].

Costs

The capital cost of the 30 MW_e BIGCC plant was estimated by CIEMAT for our previous work [2] to be 56 million US$. This equates to a specific cost of $1870/kW. Larson et al. [17] present the installed capital cost of a 30 MW_e unit as 74 million $ for the first commercial application falling to 53 million $ for the 5th application. Bressan et al. [7] estimate IGCC costs for coal feed to lie within the range 1200-1500$/kW for technical variations on the leading technologies. These figures are for units in the region of 800 MW_e; scaling down from the Bressan figures to the 30 MW_e BIGCC size, using a cost exponent of 0.7, gives a capital cost of about 100 million US$. A possible reason for the discrepancy is that earlier work on BIGCC has not fully taken into account the cost of providing a clean syngas. For example, Ciferno and Marano [6] report that the supporting processes can increase gasification costs by 70-80%. We have retained the lower capital cost figure (56 million $) used by Varela et al. [2] in this assessment.

The levelised cost of electricity from the BIGCC power station is calculated to be 8.1 cents/kWh at a 10% discount rate over a 30 year lifetime (which coincides with 2 plantation-cycles of 15 years; assuming a more standard 25 year lifetime makes little difference to the cost of electricity).

The cost of producing the SRC is 54$/dry tonne. There is a large range in the reported cost of biomass feedstocks. Ciferno and Marano quote a range for woody biomass of 16-70$/dry ton [6], noting that the cheapest sources are wood residues. The cost of biomass feed is a significant factor in the cost of producing electricity. Varela et al.[2] report that, in the 28 power generation schemes they assessed for IEA GHG, the SRC biomass cost between 40-60 $/tonne on a dry basis (approx. 2-3$/GJ on a lower heating value basis). By-product/residue biomass could be less expensive. This is examined later when discussing by-product black liquor from a paper pulp mill and sugarcane byproducts.

CO_2 and other emissions

The BIGCC emits 216,000 t/yr of CO_2 to atmosphere. Other emissions are significantly less, e.g. about 26t/yr of SO_2 and 8t/yr of particulates. The SRC used is a mixture of acacia and eucalyptus; Table 2 presents an ultimate analysis.

TABLE 2: ULTIMATE ANALYSIS FOR SRC FEED TO BIGCC

	C	H	O	N	S	Ash
Acacia	50.7	5.7	41.9	0.6	0.01	1.0
Eucalyptus	48.3	5.9	45.1	0.15	0.01	0.5

The net emission factor for the overall cycle of growing and power generation is 7gCO_2/kWh. This is very small, and for the purposes of this paper, is regarded as zero.

APPLICATION OF CO_2 CAPTURE TO BIOMASS GASIFICATION

Additional processing for CO_2 capture

As can be seen in Figure 2, the CO_2 content of the BIGCC syngas is only about 10% by volume (the CO_2 contains about 18% of the carbon in the syngas). The balance is still in the form of fuel (CO, CH_4). These syngas composition figures are taken from Ciferno and Marano [6] for a Foster Wheeler (FW) circulating fluidised-bed gasifier. Different gasifiers and process conditions alter syngas composition but the FW unit can be taken as typical.

The low CO_2 concentration in gas turbine exhausts makes the option of post-combustion CO_2 capture not very attractive. Pre-combustion capture of CO_2 is therefore assumed. A shift-conversion step is added to the process ($CO + H_2O \leftrightarrow H_2 + CO_2$) to increase the quantity of CO_2 available for capture. Almost total conversion of the CO can be achieved. In addition to the cost penalty for the shift reactor unit there is an energy penalty mainly due to the large quantities of steam required. Various commercially available solvents can be used to capture the CO_2.

The presence of nitrogen as nearly 50% of the syngas is a major processing disadvantage because in effect it is a diluent doubling the amount of gas to be processed. However, air is the most widely used oxidant in biomass gasification because it avoids the cost and energy penalties associated with producing oxygen. The main disadvantage is the low calorific value of the syngas of about 4-7MJ/Nm^3. If oxygen were to be used in the gasifier a medium heat value gas can be produced, with a calorific value of 11-13MJ/Nm^3. The relative merits of air and oxygen gasification were much debated for coal gasification but have now clearly been decided in favour of oxygen. It is possible that commercial BIGCC units may also favour oxygen. Given the above, an oxygen-blown gasifier was selected for use with the CO_2 capture BIGCC. It was assumed that an air separation unit (ASU) would be used, although a pressure-swing adsorption unit is a possibility.

Syngas produced in the BIGCC without CO_2 capture contains an appreciable amount of methane. This normally has the useful attribute of raising the calorific value of the gas. About 26% of the carbon present is contained in the methane. Methane in the syngas is not desirable in the case of CO_2 capture as it would pass through the shift reforming process and reduce the quantity of carbon available for capture. Steam reforming ($CH_4+2H_2O \leftrightarrow CO_2+4H_2$) is a possibility but would add to the complexity and cost of the process. We assume that a gasifier minimising CH_4 production can be selected; the higher temperatures achieved with oxygen blowing should make this possible. However, this potential problem should not be overlooked; only one of the 15 gasifier processes surveyed by Ciferno and Marano [6] did not produce significant amounts of methane (namely the, now abandoned, Stein Industrie process).

The problem of syngas cleaning for use as a turbine fuel becomes more acute if a shift-conversion unit is installed as the catalyst needs to be protected from tars, particulates, and potential catalyst poisons such as volatile alkali metals. This is also the case for the CO_2 capture solvent. Stevens [8] discusses syngas conditioning requirements in detail. There is an on-going debate about the effectiveness of wet scrubbers. Maniatis [5] notes that the wet scrubbing approach has proved inadequate as it produces large quantities of condensate requiring disposal in an environmentally acceptable manner. At the Värnamo plant an attempt was made to avoid the problem by keeping the syngas above 400C. This is not possible if a liquid solvent is to be used to capture CO_2. The approach adopted for the ARBRE demonstration project was to install a second circulating fluidised bed reactor of similar dimensions to the gasifier. This unit contained calcined dolomite and acted as a tar cracker. For the purposes of this paper we assume that oxygen-blowing will help to reduce the clean-up problem and that a combination of hot gas cyclones, filtration, and wet scrubbing will be adequate treatment. Figure 3 illustrates the BIGCC process including the modifications required to capture CO_2. Key input and output figures are given.

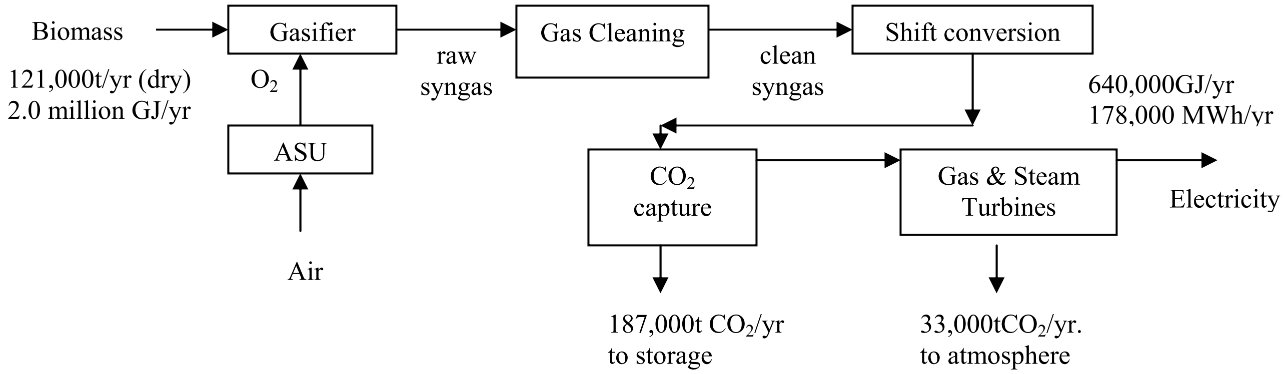


Figure 3: Biomass integrated combined cycle (with CO_2 capture)

An on-site facility to compress CO_2 is needed if it is to be transported to a permanent store. As compression to the region of 100bar is required the cost and power requirement for the compression unit are significant.

Efficiency

Previous calculations by IEAGHG, in particular the recent work on coal IGCC reported by Bressan et al.[7], indicate that the adoption of CO_2 capture and compression incurs an energy penalty of about 8% points. The penalty would not be less for BIGCC, and we have therefore assumed that the BIGCC plant with CO_2 capture has an efficiency of 32% (c.f. the 40% assumed originally for a future commercial unit). The $30MW_e$ unit becomes, therefore, a $24MW_e$ unit for the same quantity of biomass feed.

Costs

The overall capital cost of the BIGCC plant with CO_2 capture is estimated to be 101 million US$. Table 3 illustrates the breakdown of BIGCC capital costs with and without CO_2 capture and compression. The cost figures have been adapted from several IEAGHG studies. The levelised cost of electricity from the BIGCC power station was calculated to be 15.5cents/kWh at a 10% discount rate over a 30 year lifetime.

TABLE 3: CAPITAL COST ESTIMATE

Process unit	**BIGCC (no capture)**	**BIGCC (CO_2 capture)**
Gasifier	13	13
Turbines	11	9
Boiler plant and gas cleaning	4	5
Feed preparation	4	4
Air separation unit	-	14
Shift conversion	-	10
CO_2 absorber and recovery unit	-	13
CO_2 drying and compression	-	3
Balance of plant; inc. utilities, electrical & grid connection, water treatment, etc	24	30
TOTAL (millions $)US	**56**	**101**

The cost of CO_2 capture is 53$/t. It should be noted that the cost of CO_2 avoided is different (see the later discussion on cost of emission reduction). This cost is higher than estimated capture costs for coal gasification. In the work reported by Bressan et al. [7] the cost of CO_2 capture is 13$/t for an option based on a Texaco gasifier.

CO_2 balance

The biomass feed to the power station contains carbon equivalent to removing 216 000 tCO_2/year from the atmosphere (see Figs. 2 and 3). It is assumed that the CO_2 absorption unit can capture 85% of the CO_2. Hence, 32 000 tCO_2/year are returned to atmosphere and 184 000 tCO_2/year are captured and sent to a permanent store. This 184 000 tCO_2/year is a net removal of CO_2 from the atmosphere by the overall process cycle. It can be thought of as a 'negative emission', and is equivalent to –1030gCO_2/kWh. (a modern coal-fired power station emits about + 800gCO_2/kWh). Care in the use of this figure is required as the less efficient the biomass process the greater is the negative emissions per kWh of electricity.

CO_2 STORAGE AND TRANSMISSION

Storage

The quantity of CO_2 to be stored is 184 000 tonnes/year for 30 years, i.e. a total of 5.5 million tonnes. In relation to current plans for CO_2 storage, this is not a large quantity; much of the literature on underground storage of CO_2 is based on stores with capacities of 100s of millions tonnes. In the 'Stand-alone' context the CO_2 is stored deep underground in a local dedicated store and the co-incidence of a suitable store and biomass site is needed.

A small store is likely to be relatively costly per tonne of CO_2 because many of the pre-operation, operational, and closure costs are largely fixed e.g. seismic and other geological surveys, well drilling and completion, injection rate testing, CO_2 leak monitoring, etc. Bock et al., [10] gives cost estimates for storage in an aquifer that range from 1.1 - 11.7 $/$tCO_2$; the mid-range is 2.9 $/$tCO_2$. Kaarstad [11] gives a breakdown of costs for the Snovit project in which 700 000 tCO_2/year is to be stored off-shore using a single injection well. The capital cost of the drilling and well completion activities and the facilities total about 40 million US$. Adapting Kaarstad's capital cost estimates to on-shore figures using IEA GHG data [9], and adding preliminary in-house data on monitoring costs, we calculate the cost of storage in the small local store to be 9$/$tCO_2$. Shared storage in a '$CO_2$ intensive' context is likely to be significantly cheaper, say, 2$/$tCO_2$ from Bock et al. [10].

Transmission

The cost of transporting CO_2 by pipeline (or other means) is highly dependent on the quantity and distance. This is illustrated in Table 4 which has been produced using information available from IEA GHG[9].

In the context of a 'Stand-alone' development we assume the power plant is adjacent to the CO_2 store and the transmission costs are negligible (in comparison, the average crop transport distance is 25km.).

In the 'CO_2 intensive' context we assume that the captured CO_2 is stored in a large store and the costs shared with others. The captured CO_2 is transported about 25km to a CO_2 pipeline network (at a cost of 2\$/tCO_2) and then transported 500km in a pipeline conveying 5 million tCO_2/year (at a cost of 5\$/tCO_2) giving a total transmission cost of 7\$/tCO_2.

TABLE 4: COST OF CO_2 TRANSPORT BY PIPELINE

Cost of CO_2 transport by pipeline (US\$/tCO_2)			
Rate (t/yr)	**Length of pipeline (km)**		
	25	**100**	**500**
200 000	2	7	32
500 000	1	3.8	17.6
1 million	0.7	2.5	10.4
5 million	0.64	1.4	4.7

Cost of storage and transmission

From the above discussion, it can be seen that, whilst a small local store avoids the cost of CO_2 transmission, it incurs investment and monitoring cost penalties. On the other hand, a shared remote large store has cheaper storage costs but incurs a significant transmission penalty. The net result is that, in both cases, the total cost of storage and transmission is about 10\$/tCO_2.

CO_2 EMISSION REDUCTION AND COSTS

Figure 4 plots the costs and CO_2 emissions from the BIGCC power plant with and without CO_2 capture. Figures for Texaco-type coal IGCC taken from the work reported by Bressan et al. are also shown [7]. These are also shown in Table 5. In both the CO_2 capture cases the cost of CO_2 transmission and storage equates to a 1c/kWh increase in the cost of electricity.

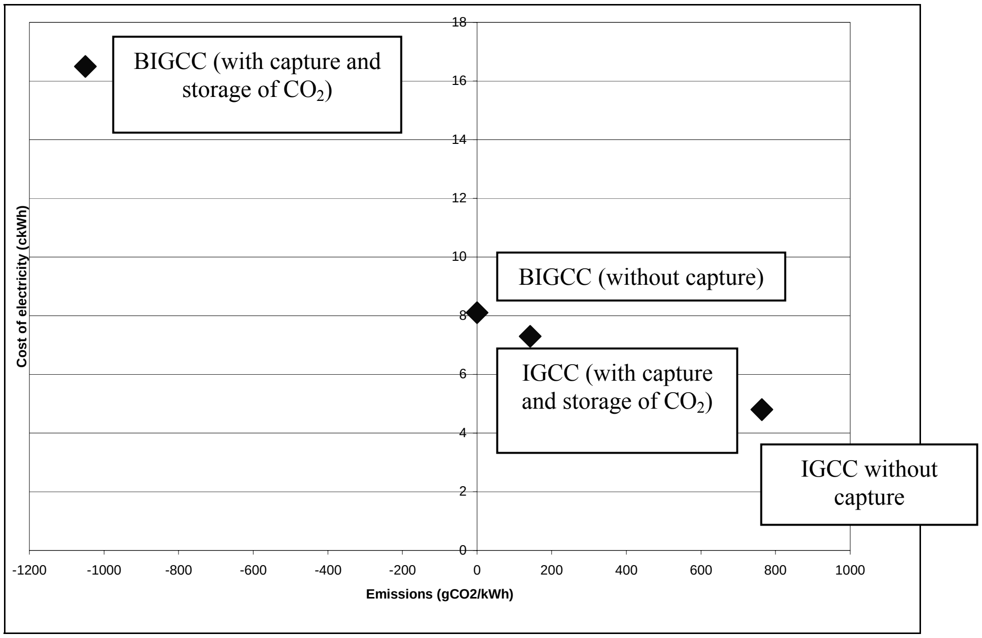


Figure 4: Electricity costs and CO_2 emissions

Figure 4 can be used to derive costs of avoiding CO_2 emissions by comparing power generation options. For example, the cost of electricity produced in the IGCC without CO_2 capture is 4.5 c/kWh. If CO_2 emissions are avoided by producing the electricity in a BIGCC without CO_2 capture at a cost of 8.1 c/kWh, the cost of avoidance is 43\$/tCO_2. (The cost of avoidance is the slope of the line between the two points.) For BIGCC, the cost of avoidance is calculated by comparing the two BIGCC points (with and without capture). The cost of electricity from a BIGCC with capture and storage is 16.5c/kWh compared to BIGCC electricity at 8.1 c/kWh giving a cost of 82 $/tCO$_2$-avoided in the atmosphere. Comparing a BIGCC with CO_2 capture with the IGCC gives a cost of avoidance of 64 $/tCO$_2$.

TABLE 5: COST OF POWER GENERATION WITH AND WITHOUT CAPTURE AND STORAGE OF CO_2

Process	**Cost of electricity (c/kWh)**	**CO_2 emission (gCO$_2$/kWh)**
BIGCC (no CO_2 capture)	8.1	Nil
BIGCC (CO_2 capture)	16.5	(Net reduction: 1050 gCO$_2$/kWh)
IGCC (no CO_2 capture)	4.8	763
IGCC (CO_2 capture)	7.3	142

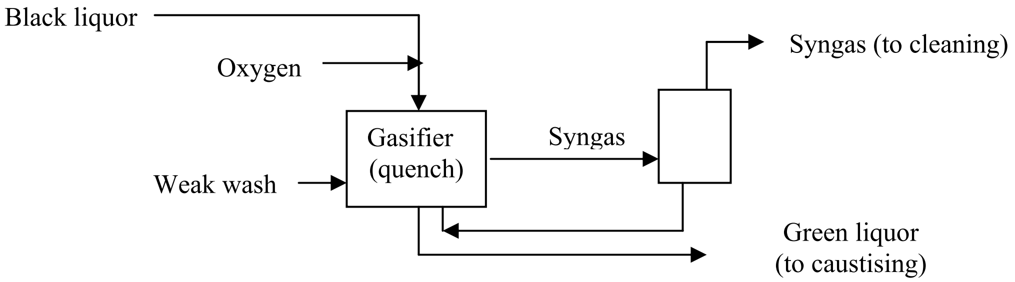
Cost of electricity in capture cases includes 1c/kWh for transmission and storage
Coal is 1.5$/GJ. IGCC uses a Shell-type gasifier

POTENTIAL BY-PRODUCT OPTIONS

Paper Pulp Mills

The potential use of BIGCC in paper pulp mills has been recognised for many years. Williams and Larson [12] note that Kraft pulp mills are significant producers of 2 forms of biomass energy. One is woody residues (bark and sawdust) produced during feed preparation. The other, referred to as black liquor, is a caustic solution containing lignin that is produced during the extraction of cellulose. Wood residues left in the forest during harvesting are potentially a third source of biomass. Wall [13] presents a detailed Sankey diagram showing energy and exergy flows through a Swedish paper mill. He notes that the combustion of black liquor does not provide sufficient steam and electricity for the mill. Although existing paper mills produce only about 60% of their electricity needs, it is frequently suggested that they could become self-sufficient by adopting BIGCC technology. Supplementing the biomass available by increasing the recovery of forestry residues may be necessary [14]. We do not examine here the potential for BIGCC use in paper mills. However, we do examine in outline the likely costs and benefits of adding CO_2 capture and storage to the BIGCC part of the process. This is done by applying the costs of treating syngas to capture CO_2 (as presented earlier for a free-standing power station) to the black liquor syngas. We discuss the costs of CO_2 capture, not the cost of CO_2 emission avoided as this requires a non-avoidance reference. In practice, it is probable that any potential application of CO_2 capture technology at a paper mill would be at an existing facility. Such retrofit applications need to be considered individually for the overall process as, for example, efficiency improvements at the paper mill may be required to compensate for the efficiency losses in CO_2 capture.

It is important to note that the gasification of black liquor has 2 purposes. The first is to produce a synthesis gas that can be burnt in a combined cycle to produce electricity. The second is the recovery of the caustic chemicals used in the digestion of the wood chips. Figure 5 illustrates the gasifier feed and products. It is based on the Chem-rec process [15]. The black and green liquor compositions are from Wall [13].



	H_2O	H	C	O	Na_2CO_3	$NaOH$	Na_2S
Black liquor	*39.6*	*3.3*	*18.8*	*16.3*	*4.2*	*11.5*	*7.2*
Green liquor	*80.8*	-	-	-	*14.0*	-	*5.2*

Figure 5: Black Liquor Gasification

The addition of a CO_2 capture step to this process would require the same processing units listed previously in Table 3 for BIGCC. In both cases, the additional processing units are shift conversion, CO_2 absorption and recovery, and CO_2 compression. However, it is not necessary to add an oxygen plant for CO_2 capture from black liquor syngas as the gasifier is already oxygen-blown. The 2 syngases are similar as they are both derived from wood (see compositions in Table 2 and Figure 5). Hence, the process can be regarded as equivalent to that described earlier for BIGCC in which the cost of CO_2 capture is 53\$/tCO_2. As the cost of the oxygen plant for black liquor gasification is included in the paper mill's economics, the cost of CO_2 capture from the black liquor syngas will be proportionally less. We estimate this cost to be 37\$/tCO_2. As discussed earlier, storage of CO_2 in either a small local store or a remote large store will cost about 10\$/tCO_2. Bringing the total cost of capture and storage to 47\$/tCO_2 stored.

Möllersten et al.[18] examine this paper mill option in some detail, concluding that the cost of capture and storage lies between 30 and 40 \$/tCO_2 for about 1.3 million tonnes CO_2 a year captured at a mill producing 1860 air-dry tonnes of paper per day.

In a biomass 'Resource-rich' country, wood residues recovered for use at the paper mill could be considerably cheaper than the cost of SRC fuel for the BIGCC (54\$/t, 3\$/GJ). Hall et al.[16] quote an average cost of biomass from Brazilian eucalyptus plantations of 1.4\$/GJ. If the cost of fuel at the paper mill was this low it would reduce the cost of CO_2 capture to about 30\$/tCO_2.

Sugarcane Processing

The possibility of introducing BIGCC with capture and storage of CO_2 into sugarcane processing, has been suggested by several authors. In all four global energy scenarios tested by Obersteiner et al. [1] they found that CO_2 capture and storage from biomass ethanol production could make a major contributor to reducing atmospheric levels of CO_2.

Larson et al. [17] examine the application of BIGCC to sugarcane processing. They note that seasonal operation, typically less than half the year, is a major problem if adequate return is to be obtained for the BIGCC investment. They devise an off-season/on-season approach in which bagasse (crushed cane residues) and trash (leaves and green cane tops) are gasified throughout the year at a consistent rate. During the off-season more electricity is exported as there is no on-site demand for sugarcane processing. As in the paper mill processing discussed above, they suggest that process economics would be improved by increased recovery of biomass left on-site during harvesting. They estimate the cost of trash bales delivered to site to be 1.2\$/GJ.

The addition of CO_2 capture and storage to a BIGCC at a sugar mill would need the same processing equipment as the scheme discussed for paper mills. In both cases, the feed to CO_2 capture processing is a biomass-derived syngas. If the gasifier is oxygen-blown, and its costs are accounted for in the sugar mill's power generation economics, the additional cost for CO_2 capture will be similar to the figures given above for the paper mill, except for any seasonal penalty.

We note that BIGCC technology is not relevant to much of the CO_2 produced during ethanol production from biomass as it is released by the fermentation step. About one third of the carbon in the sugar (glucose) is released as CO_2. Capture of CO_2 from fermentation processes is relatively simple activity consisting, in essence, of condensing-out water and compressing the CO_2. It is already common practice in larger breweries [19]. For interest, we estimate the cost of capture and compression to 100 bar to be about 9\$/tCO_2 for an electricity cost of 5c/kWh.

CONCLUSIONS

The application of BIGCC combined with CO_2 capture and storage to the production of electricity from short-rotation woody crops results in a net removal of CO_2 from the atmosphere of about 1kgCO_2/kWh. However, this figure should be used with caution as the less efficient the biomass process the greater the potential CO_2 removal per kWh of electricity produced.

The extent of technology development required is significant. Successful development of synthesis-gas cleaning is necessary to avoid contamination of the shift-conversion catalyst, the CO_2 capture solvent, and the gas turbine. The capture technology required is commercially available for clean syngas derived from fossil fuels, but has not been demonstrated on biomass-derived syngas (the cost estimates used in this paper assume successful development of the needed technology).

CO_2 capture and storage from a BIGCC is not a cheap option. This applies to both the cost of electricity generated and the cost per tonne of CO_2 emission avoided. The cost of electricity produced in a BIGCC (8.1 US cents/kWh) is more than doubled if CO_2 is captured and stored (16.5 c/kWh). The cost of avoidance involves a comparison between options. If BIGCC without CO_2 capture is used to generate electricity that would otherwise have been produced by coal gasification the cost of avoidance is 43 \$/tCO_2. If CO_2 capture and storage is used with a BIGCC, and the comparison made with BIGCC operation without CO_2 capture the cost of avoidance is 82 \$/tCO_2. Hence, if the option is available, installation of another BIGCC is a cheaper emission reduction measure than adding CO_2 capture. For comparison, the cost of avoidance for an IGCC with and without CO_2 capture is 40 \$/tCO_2.

We considered the application of this technology in a stand-alone development in which the CO_2 is stored deep underground at the power station site. We also considered the application in a CO_2-intensive context where the CO_2

could be transmitted by a shared pipeline to a large shared store. Whilst a local store avoids transmission costs it is relatively expensive. The cost of transmission and storage totals about 10 \$/tCO_2 in both cases. The cost of CO_2 capture is approximately 50 \$/tCO_2, bringing the total cost for capture and storage to 60 \$/tCO_2. If the technology is applied in a country where intensive biomass usage for energy and other products has been established, and biomass costs have been driven down, the costs would be lower. The cost of CO_2 capture and storage at a paper mill could be reduced to about 47\$/tCO_2.

The conclusion is that BIGCC combined with CO_2 capture and storage is likely to be less financially attractive than many of the more established fossil fuel and biomass-based emission reduction options. We should, however, consider whether the ability to generate electricity with negative emissions of CO_2 might be attractive for other reasons: (a) The ability to remove emissions from the atmosphere is not unique to this technology; for example, CO_2 can be removed from air by scrubbing it with sea-water (Goldthorpe and Davison [20]). (b) The possibility of 'cleaning-up afterwards' using this technology should not be seen as a justification for delaying the introduction of emission reduction measures. This is discussed by Obersteiner et al. [1]. (c) It is possible that the technology could be used in a country that had a highly developed biomass energy industry and cheap biomass.

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