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Potential market niches for biomass energy with CO_2 capture and storage—Opportunities for energy supply with negative CO_2 emissions

Kenneth Möllersten[a,*], Jinyue Yan[a], Jose R. Moreira[b]

[a] *Department of Chemical Engineering and Technology/Energy Processes, TR 50, Royal Institute of Technology, SE-100 44 Stockholm, Sweden*

[b] *National Center of Biomass, Av. Luciano Gualberto 1289, Cid. Universitaria, 05508-900, São Paulo, Brazil*

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Abstract

The paper presents an analysis of biomass energy with CO_2 capture and storage (BECS) in industrial applications. Sugar cane-based ethanol mills and chemical pulp mills are identified as market niches with promising prospects for BECS. Calculations of CO_2 balances of BECS in these applications show that the introduction of CO_2 capture and storage in biomass energy systems can significantly increase the systems' CO_2 abatement potentials. CO_2 emissions of the total systems are negative. The CO_2 reduction potentials of these technologies are discussed in regional and global contexts. An economic assessment of each system is carried out and opportunities for cost-effective technologies for CO_2 capture, transportation and storage are identified. Furthermore, potentials for system improvements that could substantially decrease the CO_2 abatement cost are addressed.

Keywords: CO_2 capture; Biomass energy; CO_2 balance; CO_2 reduction; CO_2 abatement cost; Black liquor; Pulp mills; Fuel ethanol production; Sugar cane

1. Introduction

The third and latest assessment report of the Intergovernmental Panel on Climate Change (IPCC) states that most of the observed global warming over the last 50 years is likely to have been due to the increase in greenhouse gas (GHG) concentrations in the atmosphere. The IPCC further concludes that the stabilisation of the atmospheric CO_2 concentration requires CO_2 emissions to eventually drop well below current levels [1]. In analysing measures for reducing CO_2 emissions, the IPCC concludes [2] that none of the following measures alone would be sufficient to stabilise atmospheric CO_2 concentrations: demand reductions and/or efficiency improvements; substitution among fossil fuels; switching to renewables or nuclear energy; CO_2 capture and storage; or afforestation. Thus, in identifying strategies for mitigation of climate change, combinations of multiple technologies in all sectors must be considered.

CO_2 capture and storage technologies that could minimise CO_2 emissions from fossil fuel combustion

* Corresponding author. Fax: +43 2236/807 599 or 71313.
E-mail address: mollerst@iiasa.ac.at (K. Möllersten).

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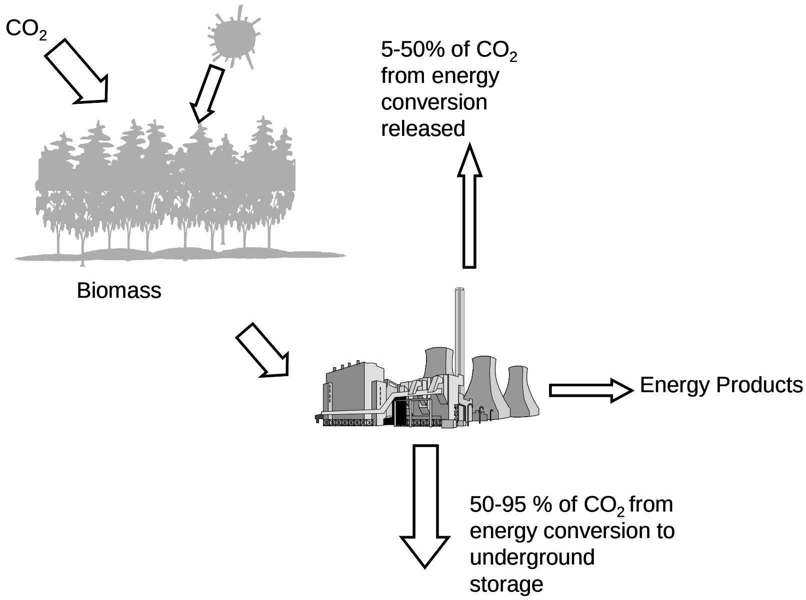

Fig. 1. Negative CO_2 emissions through biomass energy with CO_2 capture and storage.

have been discussed extensively. These technologies contribute significantly to global CO_2 emission reductions in several IPCC GHG emission mitigation scenarios [2]. However, the technologies must be further investigated regarding their reliability and safety of long-term storage, and the IPCC credits that these technologies could provide major contributions to CO_2 abatement by 2020 [2]. Nevertheless, it is important to note that fossil-based energy systems with CO_2 capture and storage will always give rise to positive net CO_2 emissions [2]. It is not technically and economically feasible to capture all of the CO_2 from a gas stream. Biomass energy with CO_2 capture and storage (BECS), on the other hand, can yield negative CO_2 emissions because the CO_2 put into storage comes from biomass and the biomass absorbs CO_2 as it grows (Fig. 1). BECS is a new concept that has received little analysis in technical literature and policy discussions (including the IPCC).

Increased interest in terrestrial carbon sink management has intensified the discussion about trade-offs between sequestering carbon in standing biomass to offset a share of fossil fuel emissions, and the increased use of biomass for fuels e.g., [3–5]. The advantage of incorporating CO_2 capture and storage into bioenergy systems is that it allows for a sustained removal of carbon from the atmosphere while simultaneously fulfilling energy needs [6]. In light of the dual role of biomass as both a fossil-fuel substitute and a carbon sink, it becomes clear that extending the discussion concerning CO_2 balances of biomass energy systems to include CO_2 capture and storage is worthwhile. Assuming that safe solutions for long-term CO_2 storage are found, BECS gives added leverage to the GHG-reduction potential of the world's biomass resources. Moreover, Obersteiner et al. [7] argued that technologies enabling rapid removal of GHGs from the atmosphere are instrumental as a climate risk management tool. This is important should unforeseen catastrophic climate-related damages start to significantly decrease human welfare. Drastically increased bioenergy use combined with CO_2 capture and storage could potentially lead to a net decrease of atmospheric CO_2 levels while sustaining a significant part of global energy and raw material demand.

In this paper, CO_2 balances of selected BECS options are presented and compared to fossil-based systems with CO_2 capture and storage. Furthermore, preliminary results of an economic assessment of CO_2 capture and storage in bioenergy systems is presented. The CO_2 reduction potentials of the selected BECS technologies are discussed in a regional and global context.

2. Technologies and potential market niches for biomass energy with CO_2 capture

Assuming that CO_2 capture and storage from mobile or small stationary sources is probably not viable for technical and economic reasons we concentrate our attention on industrial-size biomass-energy conversion facilities trying to show their suitability for CO_2 capture and storage. Today, a substantial share of large-scale biomass-energy conversion occurs for heat production or combined heat and power production (CHP) mainly in the forest products sector and sugar cane processing industries. In some countries (e.g. Sweden and Finland) large district heating plants and CHP plants are fired with biofuels. However, electric utility use of power production from biofuels remains rather low. Yan et al. [8] discuss the main challenges developing technically and economically competitive systems for biomass power generation. Future biomass-based power production technologies must be designed to provide environmental benefits at a low cost by combining biomass preparation, combustion and conversion processes with exhaust gas cleanup. Promising systems include fluidized-bed combustion, biomass-integrated gasification systems, biomass externally-fired gas turbines, and, in the long-term, hybrid fuel cells. Biomass co-firing with coal may provide a cost-effective, near-term opportunity for biomass power generation.

2.1. Technologies for biomass-based energy conversion with CO_2 *capture*

Biomass-based energy conversion with CO_2 capture can be divided into four main process groups (Fig. 2). Group 1 covers processes in which the biomass is gasified and CO_2 is captured before the hydrogen-rich fuel gas is combusted or converted to a refined liquid or gaseous fuel such as methanol. In such systems, one can opt to enhance the CO_2 capture, and improve the fuel quality, through introducing a water–gas shift reaction before CO_2 capture, whereby carbon monoxide is reacted with water to form CO_2 and hydrogen. Advanced systems and technologies for power production using hydrogen-rich fuels are under development [9]. The processes of group 2 are based on air separation to produce oxygen with the subsequent combustion of biomass in oxygen instead of air. The water in the flue gas is condensed and the remaining gaseous stream consists mainly of CO_2. A portion of the CO_2 is recirculated to moderate the combustion temperature. The technology has not been extensively demonstrated and should be regarded as long-term. Group 3, covers technically mature biomass combustion systems with CO_2 capture from the flue gases. Group 4 is the collection of CO_2 produced during biomass conversion to secondary fuels. An example is the process of sugar fermentation to yield ethanol. Through this process approximately half of the sugar mass is converted to ethanol, while the other half produces CO_2. This conversion process is carried out as the final stage of ethanol production from biomass, either from corn, sugar cane, sugar beet, or even cellulose. For the case of fermentation, essentially all gas emission is CO_2 and no further processing is needed to recover CO_2. It flows through the exhaust pipe out of the fermentation vessel, which is quite often fully covered to avoid ethanol losses due to evaporation.

Absorption is the most commonly used technology for capturing CO_2 from gas streams, whereby chemical or physical solvents are used to scrub the gases and collect the CO_2. Chemical absorption is a proven end-of-pipe method for capturing CO_2 from flue gases. When a gas is at high pressure, such as the fuel gas from pressurised gasifiers in some integrated gasification combined cycles (IGCC), physical absorption is more suitable, and relatively little extra energy is then required. The energy demand of chemical absorption is due to heat and work required for regeneration and pumping of solvent. Physical absorption consumes work for compression and pumping of the solvent. The gas separation membrane is another promising technology for CO_2 capture from gas streams, which can lead to energy and cost savings. However, much further development is necessary before this technology could be used in large-scale applications. Although there are commercially available technologies for the CO_2 capture step, the efficiency and economic performance of bioenergy with CO_2 capture can be improved through integrated process configurations,

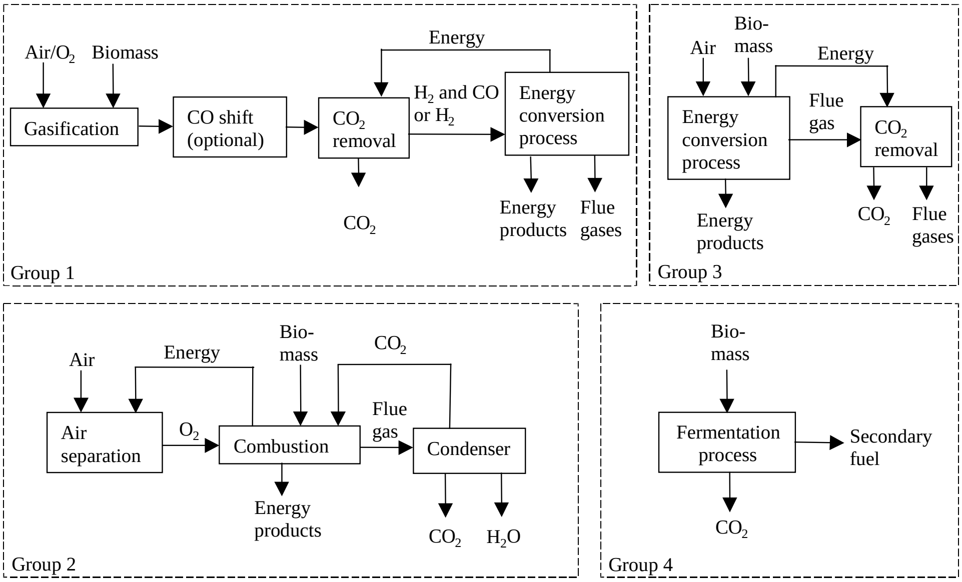

Fig. 2. Main process groups for biomass-energy conversion with CO_2 capture.

improvement of existing technologies, and the development of new technologies.

2.2. Identification of potential market niches for BECS

Today, large-scale potentials for implementing capture and storage of CO_2 from biomass can be found in the pulp and paper and cane sugar sectors, where a large portion of the current industrial conversion of biomass energy takes place. Hall et al. [10] estimated global production rates of biomass residues from maize, wheat, rice and sugar cane crops, as well as from industrial and fuelwood/charcoal obtained from roundwood. Global sugar cane and industrial roundwood residues' energy content was evaluated as 7.7 and 22.3 EJ yr^{-1}, respectively, representing 9.5 and 31.6% of all global biomass residues that were available in 1990.

In Kraft pulp mills, considerable amounts of biomass fuel in the form of black liquor are combusted in Tomlinson recovery boilers. Black liquor is a by-product of the Kraft pulping process, which is rich in lignin and cooking chemicals. The combustion of black liquor is used to recover cooking chemicals and generate steam that is used in the pulping process and that generates electricity with back-pressure steam turbines. In addition to black liquor, bark is combusted in bark boilers to satisfy the heat demand of the production process. The combustion of biofuels in pulp mills is generally large-scale and thus creates large quantities of CO_2—a prerequisite for economically feasible CO_2 capture and storage. Black liquor gasification (BLG) which is under development is an alternative to recovery boilers. The introduction of BLG would provide an opportunity to capture CO_2 by physical absorption. There are several drivers behind the development of BLG. The technology has a potential to improve the flexibility of plant capacity increases, chemicals recovery, and process safety. Moreover, it can decrease environmentally harmful emissions and increase the power-to-heat ratio in CHP systems through the introduction of IGCC [11].

The sugar industry is very large in many countries. In 2000, the total sugar production achieved 120 Mtonnes, and ethanol produced was about 30 GL. In the commercial transformation of sugar juice into sugar, not all the sucrose is used. For economical and technical reasons, related respectively, due to the large amount of energy required to extract the lowest fraction of sucrose, and due to the presence of C12 sugars not suitable for production of commercial sugar, molasses is a low-commercial value by-product of sugar production, which is used for ethanol production or to feed animals. Plants dedicated exclusively to ethanol production with sugar cane as feedstock are also in operation [12]. Typically, sugar cane processing takes place in large-scale industrial units. In Brazil, average-size plants dedicated to ethanol production can process 0.5 ML day^{-1}, with the largest approaching capacities near 5 ML day^{-1}. Since investment and operational costs of sugar plants are sensitive to economy of scale a significant participation of biomass energy in the energy matrix will imply in units able to process several ML day^{-1}, a limit constrained by the transportation distance of harvested matter. It is important to note that converting sugar plant (or starch, or cellulose) to ethanol is very energy intensive. Presently, on average, almost all the sugar cane bagasse is burned to produce electricity, mechanical power and steam for the process, making the units self-sufficient in energy. Biomass-derived CO_2 can be recovered from both the fermentation of sucrose and the combustion of residual biomass in sugar cane processing industries. A major environmental advantage of using sugar cane is the CO_2 balance of the production. When using corn, sugar beet or potatoes it is necessary to use fossil fuel during the industrial processing. Considering all agricultural activities and the processing of harvested biomass in the final product, the energy balance for alcohol production from corn is in the range of 1 to 1.5 [1] while the same relation for alcohol from sugarcane can be 8.0, leading to a substantially lower fossil fuel input [13].

3. Performance of BECS in pulp mills and ethanol mills

3.1. *Specific* CO_2 *emissions and* CO_2 *reduction potential*

The following BECS technologies were selected for in-depth examination:

- CO_2 capture by chemical absorption from the flue gases of the black liquor recovery and bark boilers in a Kraft pulp mill (post-combustion CO_2 capture).
- CO_2 capture by physical absorption from the fuel gas in a black liquor integrated gasification combined cycle (BLGCC) in a Kraft pulp mill (pre-combustion CO_2 capture).
- Capture of CO_2 from fermentation and biomass residue combustion in sugar cane-based ethanol production.

The systems are specified in Tables 1 and 2.

The specific CO_2 emissions [g CO_2 MJ_{fuel}^{-1}] for the black liquor recovery boiler with CO_2 capture specified in Table 1 were calculated and are illustrated in Fig. 3. For the purpose of comparison Fig. 3 also presents the specific CO_2 emissions for the black liquor recovery boiler without CO_2 capture and for two types of fossil fuel-based power plants with as well as without CO_2 capture.

Fig. 4 illustrates the annual CO_2 impact of the black liquor-based BECS systems defined in Table 1. The CO_2 impact relative to the systems' respective reference systems without CO_2 capture is illustrated. An analysis of the real CO_2 impact of BECS technologies requires that more than just the CO_2 capture and storage be considered. Fig. 4 illustrates not only the reductions by CO_2 capture and storage, but also the impact of the "CO_2 emission penalty" which is due to the electricity production loss induced by the capture and compression of CO_2. It was assumed that the loss in electricity production was compensated by marginal electricity produced in external coal-fired power plants [2] that emit 0.85 tonnes CO_2 MWh_e^{-1}.

In sugar cane-based ethanol production, sucrose fermentation follows the simplified chemical reaction

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 4C_2H_5OH + 4CO_2, \qquad (1)$$

where 342 g sucrose yields 184 g ethanol and 176 g CO_2. In industrial sugar production from sugar cane a typical portion, 15% of the initial sucrose, is contained in the by-product molasses which is used for ethanol production. With this information it is possible to estimate the relative mass fractions in conversion of liquid sucrose to sugar and/or ethanol that are illustrated in Fig. 5. Thus, assuming 100% capture of CO_2 from fermentation at the vessel exhaust (group 4

[1] Energy balance is defined as the net energy content of alcohol divided by the fossil energy required to produce all agricultural and processing inputs, as well as the energy used in all equipment needed for both activities.

[2] A major share of marginal electricity fed to the Swedish grid is produced in Danish coal-fired condensing steam power plants [14,15].

Table 1
Specifications of studied black liquor-based systems

	Black liquor recovery boiler and bark boiler		Black liquor integrated gasification combined cycle	
	CO_2 capture from flue gases of black liquor recovery boiler and bark boiler	Reference system without CO_2 capture	BLGCC with CO_2 capture	Reference system without CO_2 capture
Fuel input (MW) (LHV)	Black liquor 338[a] Bark 54	Black liquor 338[a] Bark 54	Black liquor 338[a]	Black liquor 338[a]
Annual operating time [days]	330	330	330	330
CO_2 capture [kg CO_2 s^{-1}][b]	34	0	14	0
Net electrical efficiency[c] (LHV)	0.10[d]	0.19	0.25[e]	0.28
Total efficiency[f] (LHV)	0.51	0.60	0.69	0.72
Additional capital cost for CO_2 capture (MUS$)	110	—	27	—

[a]The fuel input of the black liquor-based systems corresponds to a pulp production of 1550 tonnes d^{-1}.
[b]90% of the CO_2 present is captured from the boiler flue gases and from the gasifier fuel gas, respectively.
[c]Parasitic energy consumption for CO_2 capture and compression to 100 bar (liquid state, ready for transportation) has been considered. The penalty for CO_2 compression was calculated using a specific work requirement of 0.12 kWh kg^{-1} CO_2^{-1} (intercooled 5-stage compression).
[d]CO_2 is captured by chemical absorption at atmospheric pressure. The CO_2 absorption penalises the system with a heat demand of 2.9 MJ_{heat} kg^{-1} CO_2^{-1} captured for regeneration of the chemical absorbent. Five bar steam is used for the regeneration, and the power loss has been calculated assuming that the steam would otherwise have been used to run a condensing steam turbine with 20% electrical efficiency. The work requirement, mainly for pumping the absorbent, is 0.03 kWh_e kg^{-1} CO_2^{-1}.
[e]The CO_2 is captured by physical absorption from a pressurised gasifier at 28 bar. The penalty for compression and pumping of the physical solvent was calculated using a work requirement of 0.08 kWh_e kg^{-1} CO_2^{-1}.
[f](Net power output + heat to the process)/fuel input.

Table 2
Specifications of studied ethanol plant

Plant specifications	
Ethanol output (L d^{-1})[a]	10^6
Annual operating time (days)	180
CO_2 capture (kg s^{-1})	36[b]
Energy penalty for recovery of CO_2 from fermentation (kWh_e kg^{-1} CO_2^{-1})	0.12[c]
Energy penalty for recovery of CO_2 from bagasse combustion (kWh_e kg^{-1} CO_2^{-1})	0.31[d]
Additional capital cost for CO_2 capture (MUS$)	93

[a]The plant consumes around 11 ktonnes sugar cane d^{-1}. Around 1.5 Ktonnes bagasse d^{-1} (dry weight) is used as fuel to generate power and steam for the process.
[b]100% of the CO_2 from the fermentation process (9 kg s^{-1}) is recovered from the fermentation vessel. 90% of the CO_2 from bagasse combustion (or 27 kg CO_2 s^{-1}) is captured by chemical absorption from the flue gases. The penalty for CO_2 compression to 100 bar was calculated using a specific work requirement of 0.12 kWh kg^{-1} CO_2^{-1} (intercooled 5-stage compression).
[c]The CO_2 is recovered at atmospheric pressure and requires no further processing than compression (intercooled 5-stage compression).
[d]The chemical absorption penalises the system with a specific heat demand of 2.9 MJ_{heat} kg^{-1} CO_2^{-1} for regeneration of absorbent. 5 bar steam is used for the regeneration, and the penalty has been calculated as a power loss, assuming that the steam would otherwise have been used to run a condensing steam turbine with a 20% electrical efficiency. The specific work requirement, mainly for pumping the absorbent, is 0.03 kWh_e kg^{-1} CO_2^{-1}.

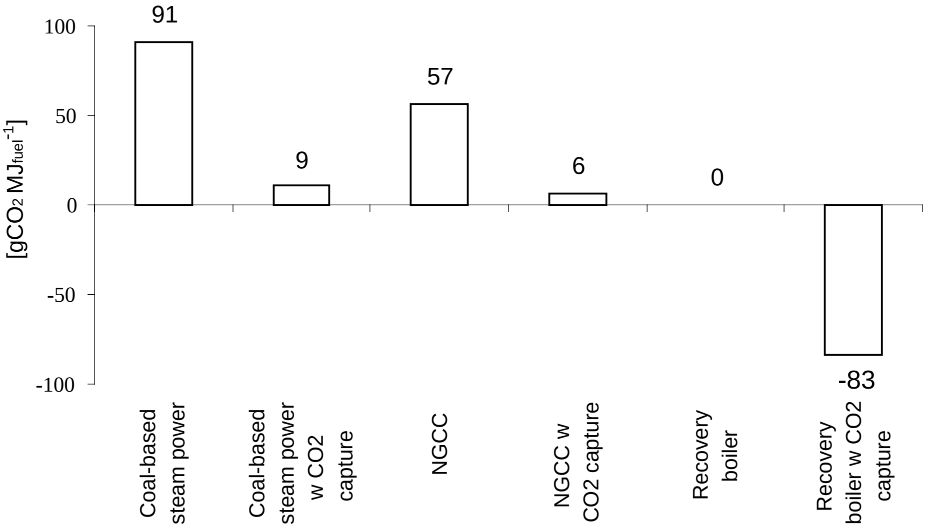

Fig. 3. Specific CO_2 emissions of fossil-based and black liquor-based systems with CO_2 capture and reference systems without CO_2 capture.

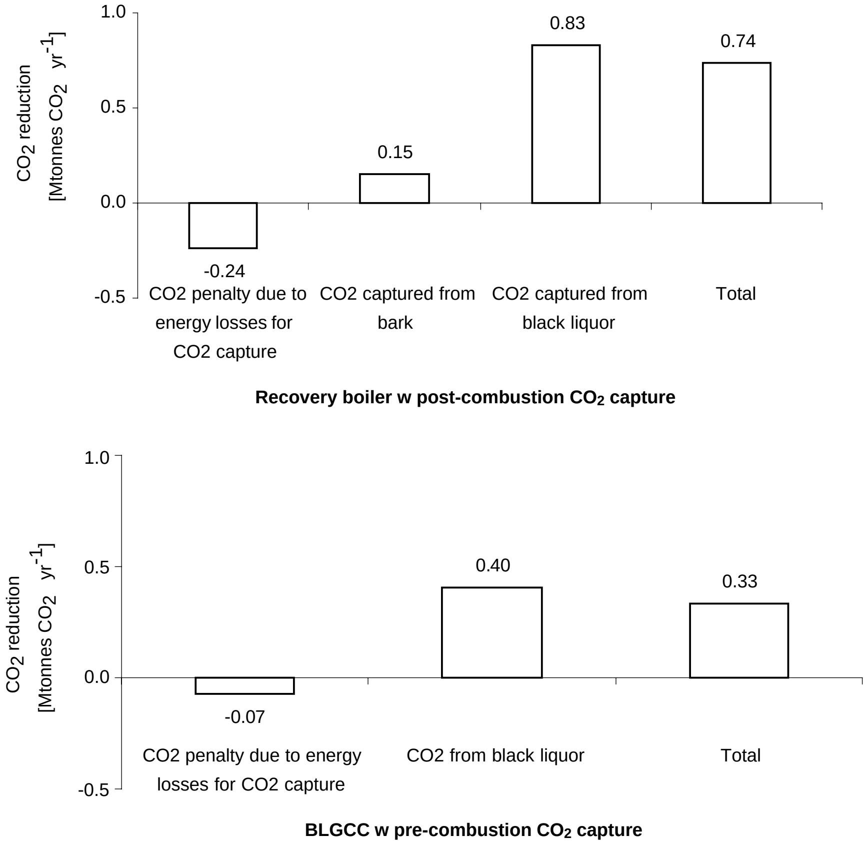

Fig. 4. Annual CO_2 reduction of studied black liquor-based plants relative to the reference systems without CO_2 capture.

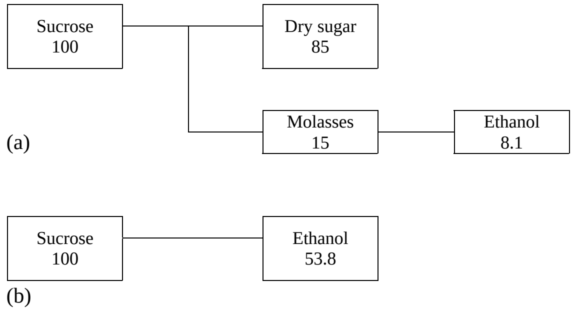

Fig. 5. (a,b). Relative mass fractions in conversion of liquid sucrose to sugar and/or ethanol.

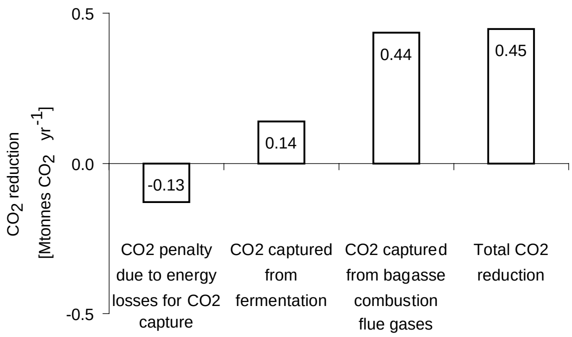

Fig. 6. Annual CO_2 reduction of ethanol production unit with integrated CO_2 capture relative to the reference system without CO_2 capture.

process) it can be estimated that 0.51 g CO_2 can be captured per g sucrose for the case of industries dedicated to ethanol production. Fig. 6 illustrates the CO_2 reduction potential of a plant dedicated to ethanol production from sugar cane with integrated CO_2 capture relative to the corresponding reference system without CO_2 capture and compression. As in the black liquor-based case the "CO_2 emission penalty" due to the electricity production loss induced by capture and compression of CO_2 was considered assuming that marginal electricity is produced in external coal-fired power plants that emit 0.85 tonnes CO_2 MWh_e^{-1}.

3.2. *The cost of* CO_2 *capture*

Table 3 presents results from a preliminary assessment of the CO_2 capture cost [US\$ $tonne^{-1}$ CO_2^{-1}] in the studied systems. The cost of CO_2 capture was calculated considering capital costs and lost electricity production (as specified in Tables 1 and 2). Other basic parameters that were used in the calculation of the CO_2 capture costs are presented in Table 4. The cost calculated for CO_2 capture in the BLGCC case is rather low compared to similar studies concerning coal-based systems e.g., [16,17]. This may partly be explained by the simple (and inexpensive) system configuration without CO-shift in the BLGCC case. The higher calculated cost of CO_2 capture in the ethanol production plant is due to high capital costs and low annual operating time. The cost comprises two parts. The first (and lower) cost is associated with the recovery of CO_2 from fermentation, and is due to the compression of the concentrated CO_2 from the fermentation vessel. It is worthwhile to mention that we are assuming the use of the current processing technology with non-pressurised fermentation vessels, but in the future ethanol processing can be made using pressurised vessels, which would imply decreased additional energy requirement for CO_2 compression. The second (and higher) cost is associated with the capture and compression of CO_2 from the flue gases from the combustion of biomass residues.

3.3. *Transportation and storage of* CO_2

The assessment of transportation alternatives requires consideration of local conditions, the rate at which CO_2 is produced, and the annual operating hours. The CO_2 transportation alternatives included in the present analysis are pipeline or tanker. The systems under consideration are characterised by fairly low CO_2 output rates (around 125 tonnes CO_2 h^{-1}). While the cost for tanker transportation is relatively insensitive to the CO_2 output rate and distance, the transportation cost for pipeline depends strongly on both the flow (due to an increasing specific investment cost with decreasing capacities) and the distance. For example, if only 50-km transportation is required, transportation with pipeline and storage can be achieved at a cost of approximately 7–10 US\$ $tonne^{-1}$ CO_2^{-1} at considered CO_2 flows [18,19]. The cost then increases by 3.5–5 US\$ $tonne^{-1}$ for every 100 km transportation. However, the annual operating time for the considered ethanol plants is low, which leads to an increase in cost by 1–2 US\$ for the initial example of 50 km transportation. Under such

Table 3
The cost of CO_2 capture

System	Cost of CO_2 capture (US\$ $tonnes^{-1} CO_2^{-1}$)
Black liquor recovery boiler w CO_2 capture from flue gases	34
BLGCC w CO_2 capture from fuel gas	23
Ethanol production from sugar cane w CO_2 capture	53

Table 4
Economic parameters used for calculating the CO_2 capture costs

Parameter	
Annual capital charge (%)	15
Scaling factor for adjusting equipment costs for size	0.7
Price of electricity (US\$ MWh^{-1})	50
Price of woody biofuels (US\$ GJ^{-1})	3
Cost for CO_2 compression of CO_2 from 1 to 100 bar (US\$ $tonnes^{-1}$ CO_2^{-1})	9

conditions, the additional cost for each extra 100 km is roughly 7–10 US\$ $tonne^{-1}$ CO_2^{-1}. If the CO_2 capture is situated by a sea or river port, transportation by tanker is feasible in many cases. An analysis by Ekström et al. [18] shows that the cost for operating a system for CO_2 storage, including transportation 700 km by tanker, amounts to 17 US\$ $tonne^{-1}$ CO_2^{-1}. The marginal cost for additional distance is then quite low.

CO_2 penalties that arise due to the energy consumption for transportation and injection of the captured CO_2 are very low. For the 50 km pipeline example above they amount to roughly 0.1 percent of the CO_2 put into storage and for the 700 km tanker example, roughly 1.5 percent of the CO_2 put into storage. These penalties are given no further consideration in this paper due to the low impact on the overall results.

4. Regional and global aspects on CO_2 reduction potentials of the studied BECS technologies

Based on the current black liquor processing of the Swedish pulp and paper sector of 131 PJ yr^{-1} (LHV) [20], our results indicate that approximately 3.8 Mtonnes C yr^{-1} could be avoided if all Swedish Kraft pulp mills were equipped with modern recovery boilers with post-combustion CO_2 capture. 3.5 Mtonnes C yr^{-1} of the reduction is due to CO_2 capture, and 0.3 Mtonnes C yr^{-1} is due to a net increase in electricity production.[3] In relation to the total annual Swedish net CO_2 emissions, the 3.5 Mtonnes C avoided represents a 25% reduction. If the recovery boilers in all Swedish chemical pulp mills were replaced by BLGCC with pre-combustion CO_2 capture (without CO-shift reaction), around 2.8 Mtonnes C yr^{-1} could be avoided (or an 18% reduction of Swedish net CO_2 emissions). Near one half of this reduction is due to additional electricity production and the other half is due to the CO_2 capture and storage. These estimates are based on the assumption that the additional electricity produced replaces electricity production in coal-fired power plants. Consequently, recovery boilers with post-combustion CO_2 capture offer a larger reduction potential than BLGCC with pre-combustion CO_2 capture. However, the cost of CO_2 capture is substantially higher for the recovery boiler alternative (Table 3).

Kraft pulp production at the global level is roughly 16 times higher than in Sweden [22]. This relationship can be used to estimate the global technical potential of black liquor-based BECS. Thus, our results suggest a global technical CO_2 reduction potential of 45–61 Mtonnes C yr^{-1}. (Within this range, lower values are for BLGCC with pre-combustion CO_2

[3] Present Swedish Kraft pulp mill CHP systems operate with an average 9% electrical efficiency [21].

capture, and higher values for recovery boilers with post-combustion CO_2 capture). This potential should rise substantially if we consider additional BECS for substitution of pulp mills' fossil-fuel combustion and purchases of electricity from the grid.

An assessment of the global technical potential for CO_2 reductions through sugar cane-based ethanol production with CO_2 capture and storage has been carried out, assuming all sugar manufactured in the world in 2001 (137 Mtonnes yr^{-1}) to be designated to fuel ethanol production. It was also assumed that all the world's fuel ethanol would be produced from sugar cane due to its environmental advantages.[4] Thus, according to Fig. 5, the additional amount of ethanol would be 96 GL yr^{-1} which shall be added to the 30 GL yr^{-1} already produced, yielding 126 GL yr^{-1} at the global level. The assumption that all sugar presently being produced would be converted to ethanol is reasonable if we consider the market potential of ethanol fuel replacing gasoline and diesel. Ethanol blended in gasoline at a proportion of 10% means a market of 81 GL yr^{-1} [23]. Moreover, considering that ethanol also can be blended in diesel at a rate of 10%, and that the global diesel consumption is of the same order as that of gasoline, the value of 126 GL assumed above is easily justified. Assuming the performance of ethanol production with CO_2 capture presented in Fig. 2, 26 Mtonnes C yr^{-1} originating from fermentation could be captured (Group 4 process). Furthermore, the resulting potential to capture CO_2 through scrubbing the flue gases from the combustion of residual biomass (sugar cane bagasse) is 82 Mtonnes C yr^{-1} (Group 3 process), thus enlarging the total direct abatement to 108 Mtonnes C yr^{-1}. Considering parasitic energy losses due to the CO_2 capture and compression and assuming that the marginal electricity on the grid is produced in coal-fired power plants, it is necessary to introduce a 22% penalty (this is illustrated in Fig. 6). Consequently, the total net reduction is 84 Mtonnes C yr^{-1}. Another contribution to carbon abatement that should be considered is the amount of fossil fuel replaced by the use of ethanol in the transportation sector. Considering, for simplicity, that all ethanol used as fuel will replace petrol, the use of 126 GL ethanol from sugar cane can replace 101 GL petrol or 65 Mtonnes C yr^{-1}. Adding this last figure to the above results, and considering a penalty for fossil fuel-input to agriculture, yields the total estimated technical global carbon abatement potential of 141 Mtonnes C yr^{-1}.

It should be noted that today, the performance of CHP in many sugar cane-processing industries is rather poor. Given sufficient economic incentives, it is possible to increase electricity generation from 15 kWh_e per tonne sugar cane processed to between 60 and 100 kWh_e per tonne sugar cane. In fact, the possibility of increasing electricity production in sugar mills is already being utilised (e.g. Brazil, China, India, Thailand [24–27]). This surplus electricity could be used as the source of the extra electricity required for CO_2 recovery from fermentation and combustion of bagasse, thus cancelling the energy penalties of 0.31 and 0.12 kWh_e kg^{-1} CO_2^{-1}, respectively (Table 2). This increases the estimated technical global carbon abatement potential from 141 Mtonnes C yr^{-1} to 165 Mtonnes C yr^{-1}.

The economic potential for CO_2 abatement through BECS in pulp mills and sugar cane-based ethanol production depends strongly on local conditions and the future carbon price. Pulp mills are generally situated by ports which means that distant transportation by tanker is usually feasible. According to our results it would therefore be possible to capture and store CO_2 from recovery boilers at an estimated cost of 50 US\$ $tonne^{-1}$ CO_2^{-1}, or at 40 US\$ $tonne^{-1}$ CO_2^{-1} if BLG is introduced. If nearby storage sites are available the cost may be reduced through transporting the CO_2 in pipelines. The cost of capturing large quantities of CO_2 in ethanol mills is higher due to the shorter operating time. Yet, if a location by a sea or river port is assumed, this study suggests that CO_2 capture and storage could be accomplished at 70 US\$ $tonne^{-1}$ CO_2^{-1}. If a storage site is nearby, or if connection to a nearby major CO_2 pipeline is possible, this cost could be reduced.

The high calculated cost for the ethanol case should be understood as valid only for a worst-case scenario. Under the assumption of intensive global use of biofuels, scale-up of ethanol mills can be expected. Moreover, there is increasing interest in producing surplus electricity to the grid almost year round.

[4] In 2001, 83.5% of all sugar produced was derived from sugar cane. The price is significantly lower for sugar obtained from sugar cane crops than from sugar beets [22].

If we assume, for example, that CO_2 is captured in a 5 ML day^{-1} unit and transported 500 km by pipeline, favourable scale effects result in a total abatement cost under 65 US\$ $tonne^{-1}$ CO_2^{-1}. If, on top of that, we assume that electricity generation is carried out also during off-harvesting season, using mainly sugar cane residues, the operating hours for the CO_2 capture could be extended to 7000 h yr^{-1}, leading to more efficient use of invested capital. In this case the abatement cost including 500 km pipeline transportation could be reduced even further to less than 50 US\$ $tonne^{-1}$ CO_2^{-1}. (3000 h yr^{-1} would involve transportation of CO_2 captured from flue gases only, which constitutes nearly 75% of the full capacity CO_2 flow.)

5. Discussion

This paper has shown that it is possible to achieve negative CO_2 emissions with BECS. However, this can only be achieved provided that the reliability and safety of long-term CO_2 storage technologies is secured. This study estimates that the accumulated C reduction potential this century for BECS in sugar mills and Kraft pulp mills amounts to 17 Gtonnes C and 6 Gtonnes C, respectively. The IPCC [3] estimates that the amount of C emissions that must be avoided during this century ranges from 300 Gtonnes C to 1500 Gtonnes C depending of the scenario. Thus, according to this study BECS in Kraft pulp mills and sugar mills could contribute to approximately 2–7% of the overall reductions needed.

The additional cost for CO_2 capture depends on the system in which the CO_2 capture technologies are applied. In power production, biomass gasification allows for lower additional CO_2 capture costs. This can become a new argument for further efforts to develop biomass integrated gasification with combined cycles (BIGCC). This paper has investigated black liquor-based BIGCC with capture of the CO_2 that is present in the fuel gas after the gasifier. This technology restricts the amount of CO_2 that can be captured to levels that are significantly lower than for post-combustion CO_2 capture. At the same time, however, the net electrical efficiency is much higher. With the introduction of a CO-shift reaction prior to the CO_2 capture in the case of BIGCC, CO_2 capture level with post-combustion CO_2 capture can be achieved. BIGCC with CO-shift, which might combine a high total CO_2 reduction with a low overall CO_2 reduction cost, should be thoroughly assessed. It should be noted that although this paper has only investigated gasification of black liquor, biomass gasification is also an option in sugar cane-processing industries where it could lead to similar advantages with respect to the power-to-heat ratio in CHP, and lower additional costs for CO_2 capture. With the use of IGCC technology, 300–500 kWh_e per tonne sugar cane processed could be achieved [28]. Consequently, the exploration of significant efficiency improvement in the conversion of sugar cane residues to electricity combined with CO_2 capture would imply a much larger technical CO_2 reduction potential than the reductions that arise from the use of ethanol.

A primary target for production of ethanol and other liquid biofuels is fossil fuel substitution in the transportation sector. However, Grassi suggests that a share of the long-term worldwide bioethanol potential, estimated at 1.6 TL of bioethanol per year, can be used by the energy sector [29].[5] Combining the utilisation of liquid biofuels in power plants with CO_2 capture and storage represents a way to enhance the CO_2 abatement potential of fossil–fuel substitution by biofuels. Moreover, such practice would present an effective solution to the problem of transporting large amounts of biomass-derived carbon fuels to sites where CO_2 can be stored.

So far, there has been a lack of integration of R&D on biomass energy and fossil energy (including carbon capture and storage-related topics). Observing that there is a need for an early assessment of possibilities to integrate BECS into the global energy supply, we argue that increased integration of biomass energy R&D with R&D related to CO_2 capture and storage is necessary.

6. Conclusions

We have discussed the potential for negative CO_2 emissions through implementation of biomass energy with CO_2 capture and storage (BECS). In principal,

[5] The high bioethanol figure assumes production of 500 Mtonnes yr^{-1} from sugar/starch crops and 1500 Mtonnes yr^{-1} from lignocellulosic biomass.

the same technologies for CO_2 capture that can be applied to coal are suitable for biomass. In addition, CO_2 can be recovered from the process of fermenting sucrose to produce ethanol. Providing that safe solutions for long-term CO_2 storage are found, BECS can give leverage to the carbon-reduction potential of the world's biomass resources. The reduction potential of BECS grows with increasing large-scale biomass energy conversion. Already at present production rates, introduction of CO_2 capture (with storage) into black liquor-based CHP in chemical pulp mills and sugar cane-processing industries could have a noticeable impact on the global CO_2 balance.

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