Capturing and Sequestering CO_2 from a Coal-fired Power Plant - Assessing the Net Energy and Greenhouse Gas Emissions

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INTRODUCTION

It is technically feasible to capture CO_2 from the flue gas of a coal-fired power plant and various researchers are working to understand the fate of sequestered CO_2 and its long term environmental effects. Sequestering CO_2 significantly reduces the CO_2 emissions from the power plant itself, but this is not the total picture. CO_2 capture and sequestration consumes additional energy, thus lowering the plant's fuel to electricity efficiency. To compensate for this, more fossil fuel must be procured and consumed to produce extra electricity. Taking this into consideration, it was desired to determine what the actual reduction in global warming potential (GWP) would be to maintain power generation capacity. To answer this, an analysis was performed at the National Renewable Energy Laboratory to examine the GWP and energy balance of coal-fired power generation which incorporates CO_2 capture and sequestration. To understand the overall environmental implications, a life cycle approach, which takes into account the upstream process steps, was applied. The reference system consisted of coal mining, transportation, and power plant operation. In order to maintain power generation capacity, additional capacity must come from another source. Two sources were examined: extra capacity from a natural gas combined-cycle system or extra capacity from the grid.

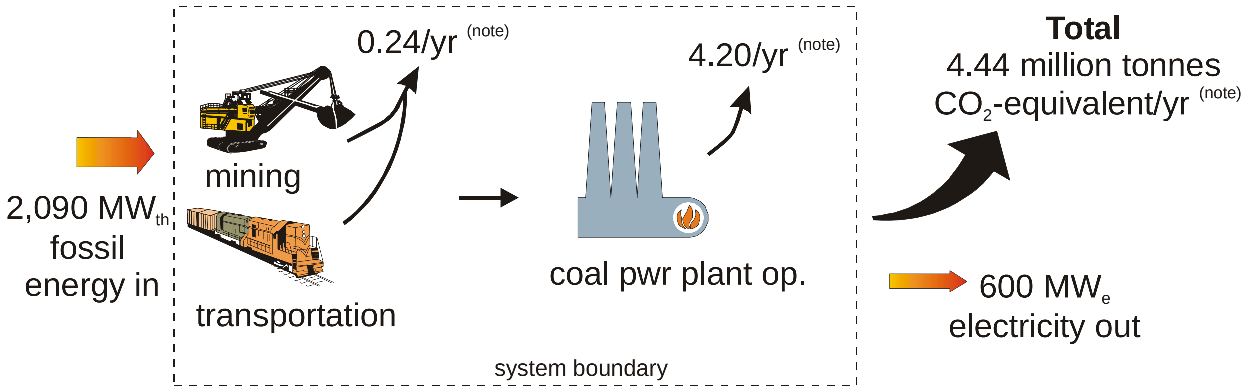
OBJECTIVE

The purpose of this analysis was to examine the GWP and energy balance of a complete power generation system which incorporates CO_2 capture and sequestration in conjunction with a coal-fired power plant while maintaining constant power generating capacity. A life cycle approach was taken because it is important to include the upstream emissions, which remain constant after CO_2 sequestration, in order to obtain the total environmental picture. Although CO_2 is the most important greenhouse gas (GHG) and is emitted from power generation in the largest quantity, quantifying the total GHG emissions is the key to determining the system's GWP. The GWP of a system is considered to be a combination of CO_2, CH_4, and N_2O emissions expressed in terms of CO_2-equivalence. According to the Intergovernmental Panel on Climate Change (IPCC), the contribution to atmospheric warming by CH_4 and N_2O is 21 and 310 times higher than CO_2, respectively, for a 100 year time frame[1]. These factors can be used to express the GWP in terms of CO_2-equivalence.

APPROACH

First, a reference system needed to be established. The reference plant is a 600 MW pulverized coal-fired power plant and the system consists of coal mining, transportation, and power plant operation prior to adding CO_2 capture and sequestration. The coal-fired power plant design and ultimately the CO_2 capture technology is the same as one given in Chris Hendriks thesis[2]. The predominant greenhouse gas emitted from coal combustion is CO_2 and there are negligible amounts of CH_4 and N_2O. The nitrogen is primarily emitted in the form of NO_x. Figure 1 shows the GWP for the reference system to be 4.44 million tonnes CO_2-equivalent/yr and the energy balance reveals that 2,090 MW_{th} of fossil energy is consumed to produce 600 MW of electricity. The GHG emissions for coal mining and transportation were taken from a previous LCA on coal-fired power production[3].

Figure 1: Coal-fired Power Plant Prior to CO_2 Sequestration (600 MW)



Note: GHGs (CO_2, CH_4, and N_2O) expressed in million tonnes CO_2-equivalents/yr at 100% capacity

After adding CO_2 capture via a monoethanolamine (MEA) system, the CO_2 was compressed, transported via pipeline, and sequestered in underground storage such as a gas field, oil field, or aquifer. CO_2 capture and sequestration consumes additional energy, therefore, in order to maintain power generation capacity, additional capacity must come from another source. Two scenarios were examined to account for the capacity loss: adding extra capacity from a natural gas combined-cycle system and adding extra capacity from the grid. The NGCC system was chosen because this type of power generation is currently being constructed and future power plants are anticipated to be NGCC. For the grid option, the mid-continental U.S. generation mix was used.

CO_2 TRANSPORT ASSUMPTIONS

To examine the effect of distance, the CO_2 transport distance was varied from 300 km to 1,800 km then the CO_2 was discharged to an underground depth of about 800 m. To recover the pipeline pressure drop, compressor stations were assumed to be at 300 km intervals. The electricity for the re-compression step was assumed to be the generation mix of the mid-continental United States, which according to the National Electric Reliability Council, is composed of 64.7% coal, 5.1% lignite, 18.4% nuclear, 10.3% hydro, 1.4% natural gas, and 0.1% oil. The greenhouse gas (GHG) emissions associated with this mix were taken from a database, known as Data for Environmental Analysis and Management (DEAM), within the life cycle assessment (LCA) software package Tools for Environmental Analysis and Management (TEAM®), by Ecobalance, Inc.

There will be emissions associated with building, drilling, and laying the pipeline. The GHG emissions for building the pipeline were taken from a previous NREL report which examined the life cycle assessment of a natural gas combined cycle power plant [4]. In this report, the emissions for constructing a natural gas pipeline were determined. These results were used in this analysis because construction of the CO_2 pipeline will be similar to assembling a natural gas pipeline.

CO_2 CAPTURE & COMPRESSION ENERGY REQUIREMENTS

Capturing the flue gas CO_2 then compressing it prior to transport consumes a considerable amount of energy. There is a power loss due to extracting the steam needed for the absorber/stripper system. Additional power is consumed in scrubbing the CO_2 due to compressing the flue gas and pumping the solvent. Finally, power is required to compress the recovered CO_2 prior to sequestration. In Hendrik's design there is a small amount of power saved because a slipstream from the reboiler replaces some cold boiler feedwater (BFW). Table 1 shows the efficiency loss and the amount of power that is required for each of the steps mentioned above. All of the steps combined result in a reduced plant capacity of 457 MW (reference case = 600 MW). The power plant efficiency prior to CO_2 capture and sequestration is 41% (LHV basis) and the new power plant efficiency with CO_2 capture and compression is reduced by 9.8 percentage points to 31.2%.

Table 1: Power Losses from Capturing & Compressing CO_2

	From steam extraction	From scrubbing (a)	From compression	From avoiding BFW pre-heating	Total
Plant efficiency loss (percentage points)	7.4	0.4	2.7	-0.7	9.8
Power loss (MW)	108	6	39	-10	143

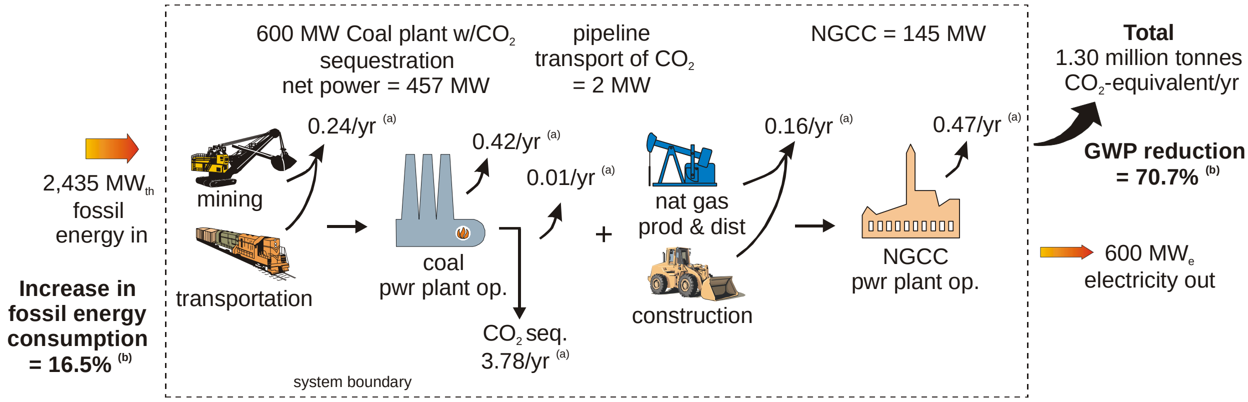
(a) Compression of flue gas and pumping of solvent.

The additional electricity requirement for re-compression along the pipeline was not subtracted from the power plant capacity because the electricity for this step comes from the grid. However, it should be noted that the electrical requirement for re-compression was accounted for in the overall system. This electrical requirement was found to be small even as the pipeline distance becomes large; at 1,800 km, the electricity requirement is only 5.7 MW. Therefore, most of the power requirements are in the CO_2 capture and compression steps (Table 1 above).

RESULTS - GWP & ENERGY FOR COAL-FIRED POWER GENERATION WITH CO_2 SEQUESTRATION

After adding CO_2 capture and compression, the capacity of the coal-fired power plant was reduced to 457 MW. Including pipeline transport, an additional 145 MW of capacity is required from another source in order to maintain 600 MW of capacity. Figures 2 and 3 give the GWP for the coal plant with CO_2 sequestration plus additional capacity from a NGCC system, and the coal plant with CO_2 sequestration plus additional capacity from the grid, respectively. A previous NREL study[4] was used to obtain the GHG emissions for the NGCC system including upstream emissions for natural gas production and distribution as well as construction emissions. For the grid option, the mid-continental U.S. generation mix as previously stated in the "CO_2 Transport Assumptions" section was used. Due to lack of data, no upstream emissions associated with power generation from lignite, nuclear, hydro, and oil were included.

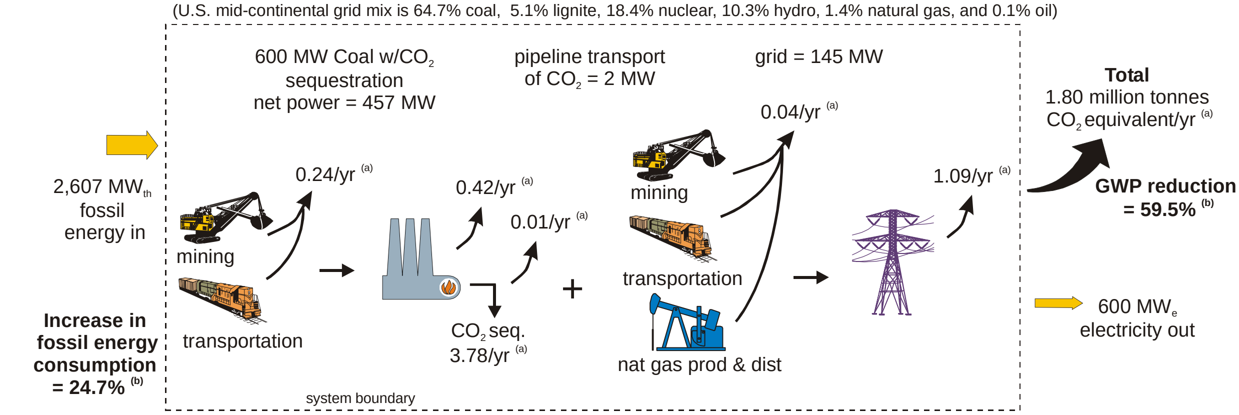
Figure 2: Coal-fired Power Plant with CO_2 Sequestration and 145 MW of NGCC Capacity Added to Maintain 600 MW



Notes: (a) GHGs (CO_2, CH_4, and N_2O) expressed in million tonnes CO_2-equivalents/yr at 100% capacity; (b) Change in GWP and change in fossil energy consumption compared to reference

Figure 3: Coal-fired Power Plant with CO_2 Sequestration and 145 MW of Grid Capacity Added to Maintain 600 MW

(U.S. mid-continental grid mix is 64.7% coal, 5.1% lignite, 18.4% nuclear, 10.3% hydro, 1.4% natural gas, and 0.1% oil)



Notes: (a) GHGs (CO_2, CH_4, and N_2O) expressed in million tonnes CO_2-equivalents/yr at 100% capacity; (b) Change in GWP and change in fossil energy consumption compared to reference

Figure 2 shows that if natural gas is used to account for the lost capacity then the net reduction in GWP from the reference system (shown in Figure 1) is only 71% and the fossil energy consumption increases by 17%. The net reduction in GWP is not as large if the additional capacity comes from the grid. However, there is still a savings of 60% with a 25% increase in fossil energy consumption (Figure 3).

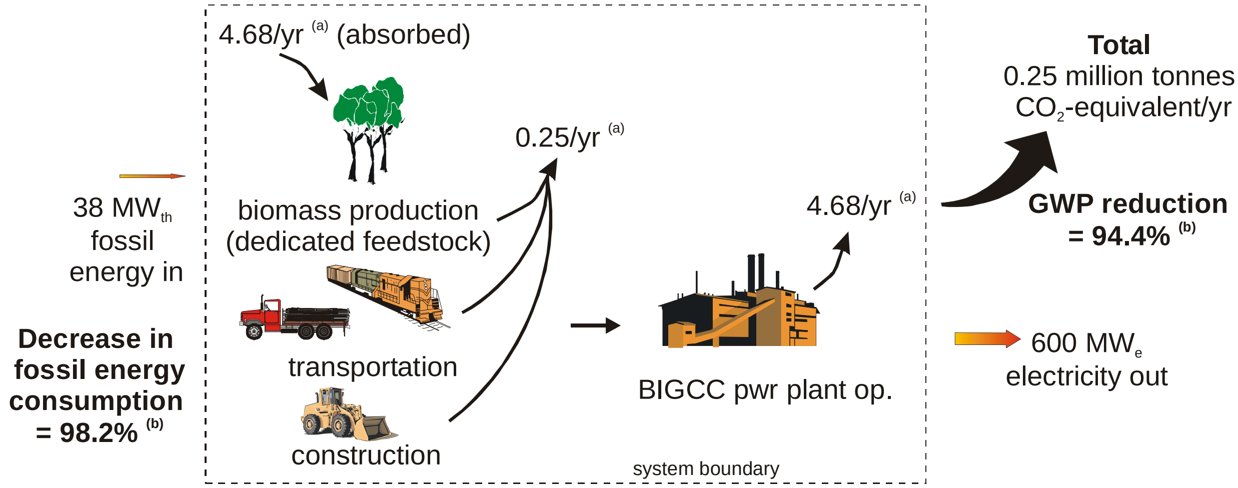
In order to further reduce the GWP of the system, CO_2 could be sequestered from successive power plants. For example, in the NGCC case, the CO_2 from the 145 MW NGCC plant could also be sequestered. In this case, the GWP for the system is reduced by 77% from the reference system (shown in Figure 1) with a 20% increase in fossil energy consumption. One could continue to sequester CO_2 from the last fossil fueled power plant but it was found that further sequestering of CO_2 reduces the system GWP and increases the fossil energy consumption by negligible amounts compared to the values stated above.

COMPARISON TO BIOMASS-BASED ELECTRICITY

Past NREL LCA studies[5,6] have shown that biomass-based electricity production has the opportunity to make significant reductions in greenhouse gas emissions per kWh of electricity produced. Figures

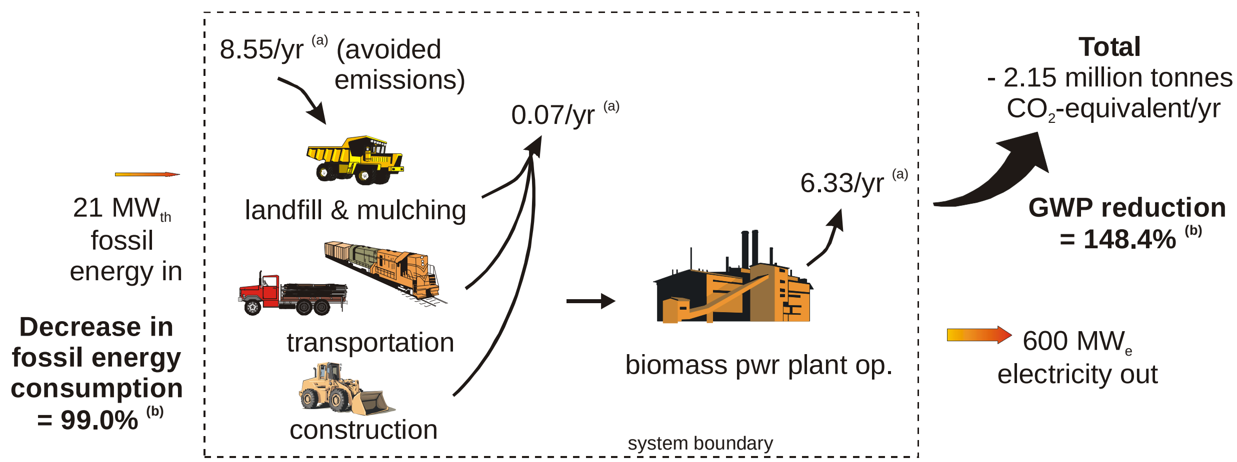
4 and 5 show the GWP and energy balance for two biomass power generation systems: 1) a biomass-fired integrated gasification combined cycle (IGCC) system using a biomass energy crop, and 2) a direct-fired biomass power plant using biomass residue.

Figure 4: Biomass Dedicated Feedstock IGCC (several plants totaling 600 MW)



Notes: (a) GHGs (CO_2, CH_4, and N_2O) expressed in million tonnes CO_2-equivalents/yr at 100% capacity;
(b) Change in GWP and change in fossil energy consumption compared to reference system

Figure 5: Bomass Residue Direct-Fired (several plants totaling 600 MW)



Notes: (a) GHGs (CO_2, CH_4, and N_2O) expressed in million tonnes CO_2-equivalents/yr at 100% capacity;
(b) Change in GWP and change in fossil energy consumption compared to reference system

These biomass systems significantly reduce the fossil energy consumption in addition to lowering the GWP of power generation per kWh of electricity produced. Table 2 summarizes the GWP and energy consumption for the fossil and biomass power systems discussed in this paper.

Table 2: Comparison of GWP and Energy Balance for Fossil and Biomass Power Systems

Case	Fossil energy consumed to produce 600 MW_e (MW_{th})	Net GWP (CO_2-equivalent/yr)	Change from reference case	
			fossil energy consumption	GWP
Coal-fired reference system	2,090	4.44	N/A	N/A
Coal w/CO_2 seq. plus NGCC	2,435	1.30	16.5%	-70.7%
Coal w/CO_2 seq. plus grid	2,607	1.80	24.7%	-59.5%
Biomass IGCC	38	0.25	-98.2%	-94.4%
Biomass direct-fired	21	-2.15	-99.0%	-148.4%

CONCLUSIONS

This analysis shows that capturing CO_2 from power plant flue gas and sequestering it in underground storage such as a gas field, oil field, or aquifer can reduce the GWP of electricity production but the penalty is an increase in fossil energy consumption. First, capturing and compressing flue gas CO_2 results in a large decrease in the power plant efficiency. Secondly, maintaining a designated plant capacity means that additional electricity production must come from another source, most likely fossil. Therefore, although there is a substantial decrease in the GWP, sequestering 90% of the CO_2 from the power plant flue gas does not equal a 90% reduction in the GWP per kWh of electricity produced. Additionally, while transportation of compressed CO_2 has been demonstrated, important issues involving safety and reliability remain prior to large scale deployment. Also, there is much debate about the fate of the sequestered CO_2 and its long term environmental effects. Although coal-fired power plant emissions are reduced considerably by capturing and sequestering CO_2, substituting electricity generated by fossil fuels with biomass electricity, will reduce the GWP along with decreasing the fossil energy consumption per kWh of electricity generated.

FUTURE ACTIVITIES

For a fixed rate of return, it is generally accepted that a biomass combined-cycle power plant will result in a higher electricity price than a coal-fired plant. However, because of the large expense for capturing and sequestering CO_2, a biomass IGCC plant becomes cost competitive with a coal plant which has incorporated CO_2 sequestration. Future analyses will be done to compare the economics in conjunction with the GWP and energy balance of biomass power to electricity production via coal plus CO_2 sequestration and even via natural gas with CO_2 sequestration. This will tell us the cost of avoiding GHG emissions by using the more expensive biomass technology over conventional fossil systems. Additionally, although we know that adding the CO_2 capture and sequestration steps to a biomass power plant will result in a negative GWP, this will be done to determine the magnitude of the negative GWP.

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