THE NET ENERGY AND GLOBAL WARMING POTENTIAL OF BIOMASS POWER COMPARED TO COAL-FIRED ELECTRICITY WITH CO_2 SEQUESTRATION - A LIFE CYCLE APPROACH

Pamela L. Spath, National Renewable Energy Laboratory, Golden, CO
Margaret K. Mann, National Renewable Energy Laboratory, Golden, CO

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 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 make up for lost capacity. Taking this into consideration, the National Renewable Energy Laboratory (NREL) examined the global warming potential (GWP) and energy balance of coal-fired power generation which incorporates CO_2 capture and sequestration assuming a constant power generation capacity is maintained. To understand the overall environmental implications, a life cycle approach, which takes into account the upstream process steps, was applied. To examine the potential environmental benefit of biomass power, the net energy and GWP of the coal system with and without CO_2 sequestration was compared to the results of previously performed life cycle assessments on two biomass power generation technologies. The biomass systems are a biomass-fired integrated gasification combined cycle (IGCC) plant using a biomass energy crop, and a direct-fired biomass power system using biomass residue.

Systems Examined

The power generation capacity of each system examined was kept constant at 600 MW. Each system includes the upstream processes necessary for feedstock procurement (mining coal, growing dedicated biomass, collecting residue biomass), transportation, and any construction of equipment and pipelines. For the cases where CO_2 is sequestered, the CO_2 is captured via a monoethanolamine (MEA) system, compressed, transported via pipeline, and sequestered underground in a storage medium such as a gas field, oil field, or aquifer. The energy requirements for capturing and compressing the CO_2 were subtracted from the gross output of the power plant. The CO_2 transport distance was varied from 300 km to 1,800 km, to examine the effect of distance, then the CO_2 was discharged to an underground depth of about 800 m. Compressor stations were assumed to be at 300 km intervals to recover the pipeline pressure drop. Emissions and energy use associated with re-compression along with building, drilling, and laying the pipeline were included in the analysis. The results showed that even at the longer distance of 1,800 km the electrical requirement for re-compression is small compared to the power consumption for CO_2 capture and compression at the power plant so the results presented in this paper are for a pipeline distance of 600 km.

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 (NGCC) system and adding extra capacity from the grid. For simplicity and because there is not a large difference in the results, adding extra capacity from a NGCC system is the only option presented in this paper. Additionally, NGCC is the type of power generation that is currently being constructed and future power plants are anticipated to be NGCC. The GHG emissions and energy consumption for the NGCC system were taken from a previous NREL life cycle assessment [1]. The following table lists the systems and cases discussed in this paper.

Table 1. Systems and Cases Examined

System	Case	
	System prior to CO_2 sequestration	System with CO_2 sequestration and extra capacity from NGCC
Coal-fired	1	1A
Biomass direct-fired	2	2A
Biomass IGCC	3	3A

Coal-fired Systems

The reference plant (Case 1) 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 sequestration. The data for this system was taken from two sources: [2] and [3]. Figure 1 shows the GWP for the coal 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. Note, for all of the figures the GWP is given at 100% operating capacity.

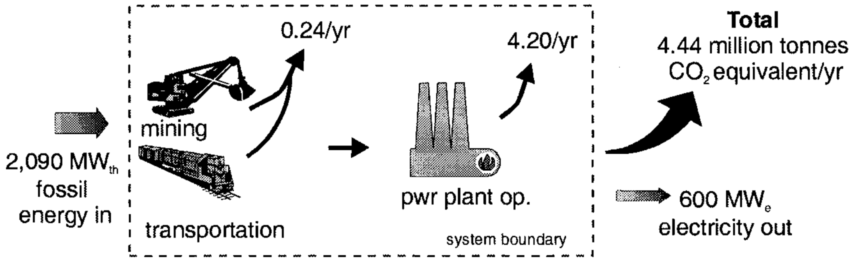

Figure 1. GWP & Energy for Coal Reference System (Case 1)

After adding CO_2 capture and compression, the capacity of the coal-fired power plant is reduced to 457 MW. Including pipeline transport, an additional 145 MW of capacity is required from NGCC power generation in order to maintain 600 MW of capacity. Figure 2 shows the GWP for the coal plant with CO_2 sequestration plus additional capacity from a NGCC system (Case 1A). The GWP for the coal system with CO_2 sequestration (Case 1A) is 1.30 million tonnes CO_2-equivalent/yr which is a 71% reduction from the reference system shown in Figure 1 (Case 1). To maintain constant capacity, the fossil energy consumption increases 16% from Case 1.

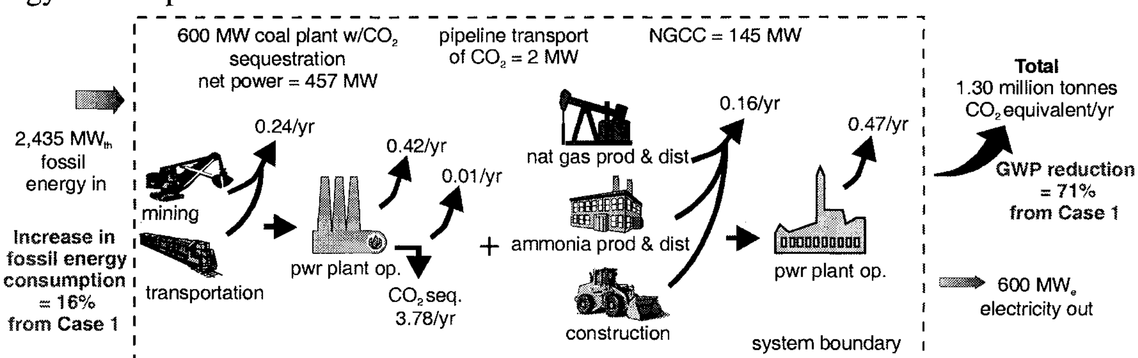

Figure 2. GWP & Energy for Coal System with CO_2 Sequestration (Case1A)

Direct-fired Biomass Systems

The first biomass power system examined in this analysis is a direct-fired biomass power plant using biomass residue as a feedstock (Case 2). This is representative of today's current technology. The data for this system was taken from a previous NREL study [4]. Because large transportation distances render large-scale biomass power plants uneconomical, it is assumed that several small plants are needed to achieve 600 MW of electric capacity. The biomass is assumed to be produced by urban sources and diverted from normal landfilling and mulching operations.

Because biomass is diverted from its normal routes of disposal, methane and CO_2 that normally would be produced through decomposition are avoided (See [5] - Avoided Operations). These avoided emissions are taken as a credit in the GHG emissions inventory for the direct-fired system. Because of this, the system (Case 2) results in a negative GWP of -2.15 million tonnes CO_2-equivalent/yr and the fossil energy consumption is 21 MW_{th}, as shown in Figure 3. The GWP is a 148% reduction from the coal reference system (Case 1) and the fossil energy consumption is reduced by 99%.

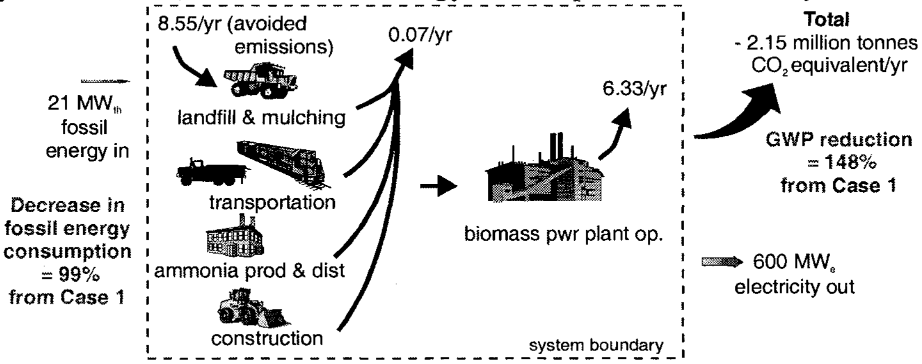

Figure 3. GWP & Energy for Biomass Direct-Fired System (Case 2)

Although the GHG emissions for the direct-fired biomass system are already negative, applying CO_2 sequestration to this system will decrease the net GWP even more. Figure 4 shows the GWP and energy balance for the direct-fired biomass system with CO_2 sequestration at constant power generation capacity (Case 2A). The GWP is reduced to -7.19 million tonnes CO_2-equivalent/yr which is 262% lower than the coal reference system (Case 1). The fossil energy consumption is now 371 MW_{th} but this is still lower than the coal reference system (Case 1) by 82%.

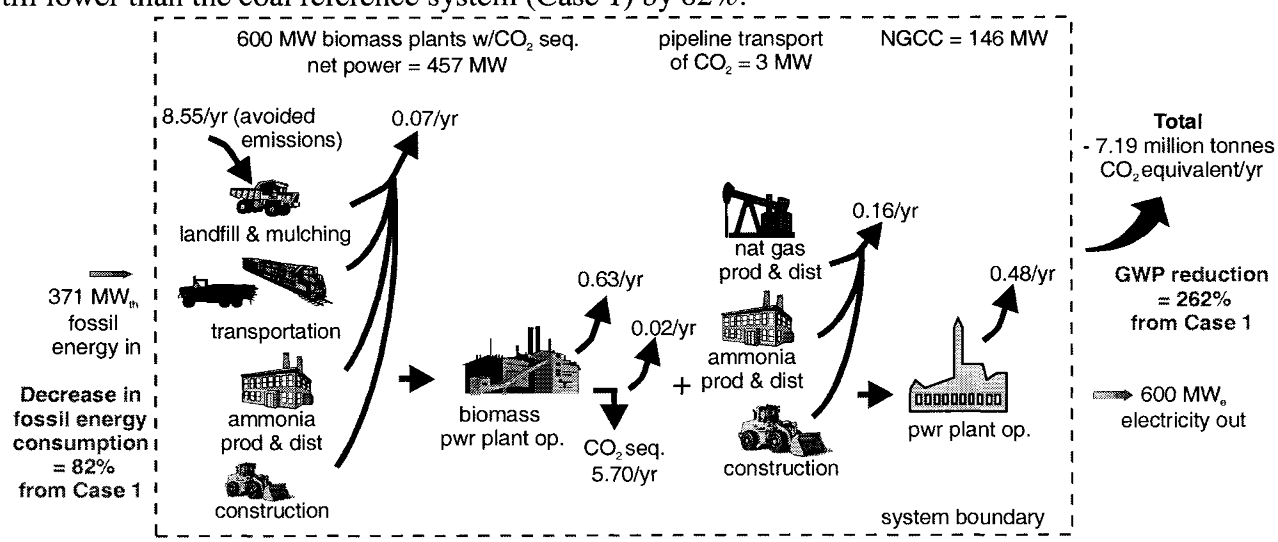

Figure 4. GWP & Energy for Biomass Direct-Fired System with CO_2 Sequestration (Case 2A)

Biomass-fired Integrated Gasification Combined-Cycle Systems

The advanced technology biomass power production system examined in this analysis implements a biomass-fired integrated gasification combined cycle (IGCC) system using a biomass energy crop. Again, the data for this system came from a previous LCA [6] and it is assumed that several small plants would be needed to produce 600 MW of electricity. Figure 5 shows the GWP and fossil energy consumption for this system to be 0.26 million tonnes CO_2-equivalent/yr and 38 MW_{th}, respectively. Because CO_2 emitted from the power plant is recycled back to the biomass as it grows, the net GHG emissions from this system is only 6% of those from the reference coal system (Case 1). Additionally, because of the renewable feedstock source, the fossil energy consumption is 98% less than the coal reference system (Case 1).

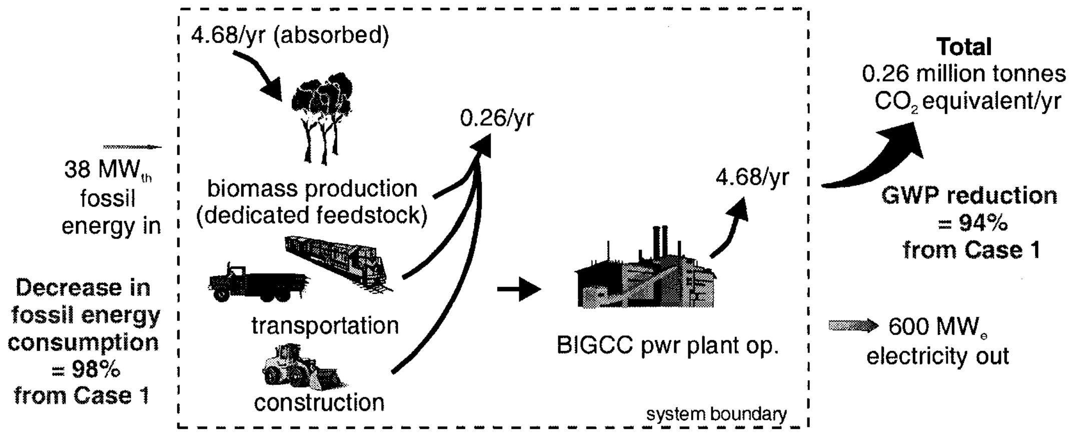

Figure 5. GWP & Energy for Biomass IGCC System (Case 3)

If CO_2 sequestration is incorporated into this biomass power generation system, then the net GWP will be negative. As can be seen in Figure 6 (Case 3A), the GWP is reduced to -3.50 CO_2-equivalent/yr which is a 179% reduction from the coal reference system (Case 1). Additionally, the fossil energy consumption is still considerably less than the coal reference system at 275 MW_{th} (an 87% decrease from Case 1).

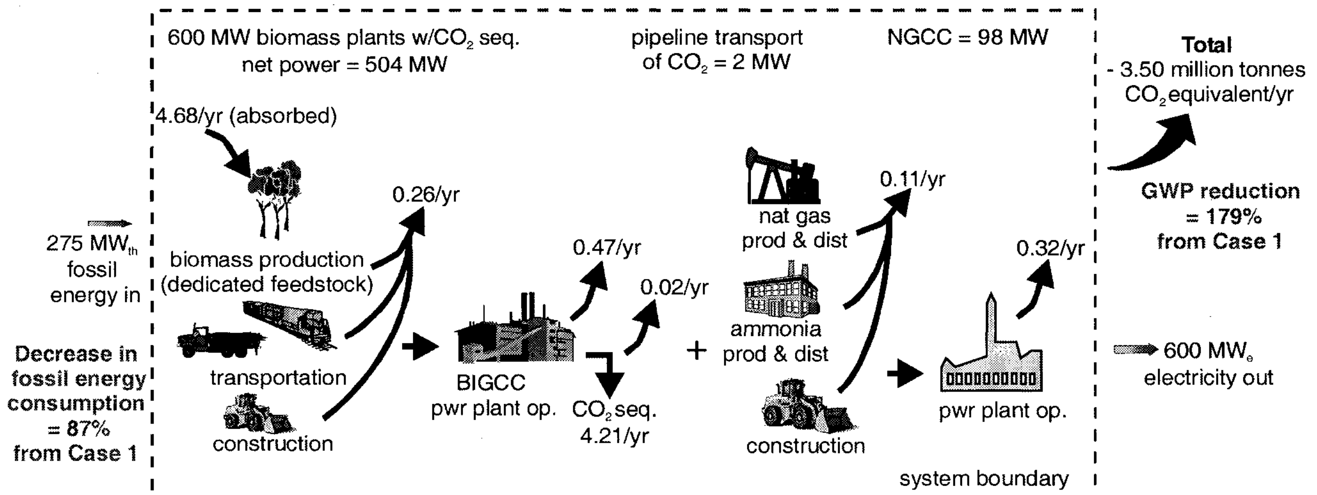

Figure 6. GWP & Energy for Biomass IGCC System with CO_2 Sequestration (Case 3A)

Summary of GWP and Energy Balance for Coal and Biomass Systems

Figures 7 and 8 summarize the GWP and energy balance, respectively, for the coal and biomass systems discussed in the previous sections. Even with CO_2 sequestration, the amount of GHG emissions per the same amount of electricity production is more for the coal-fired system than for the biomass power generation systems. Additionally, the fossil energy consumption is significantly more for the coal systems.

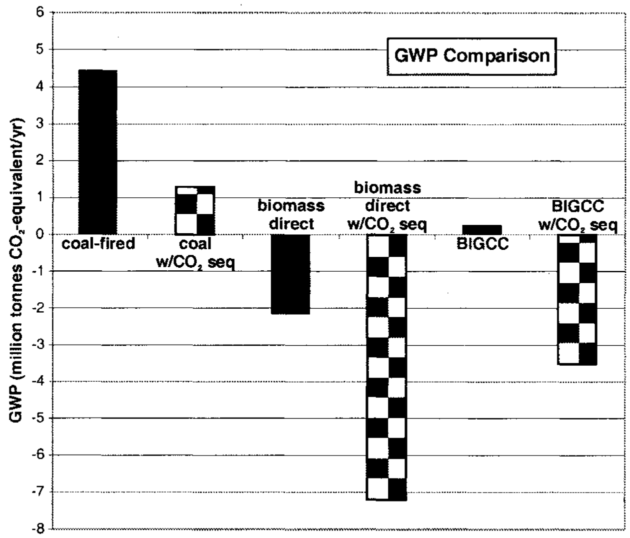

Figure 7. Comparison of GWP

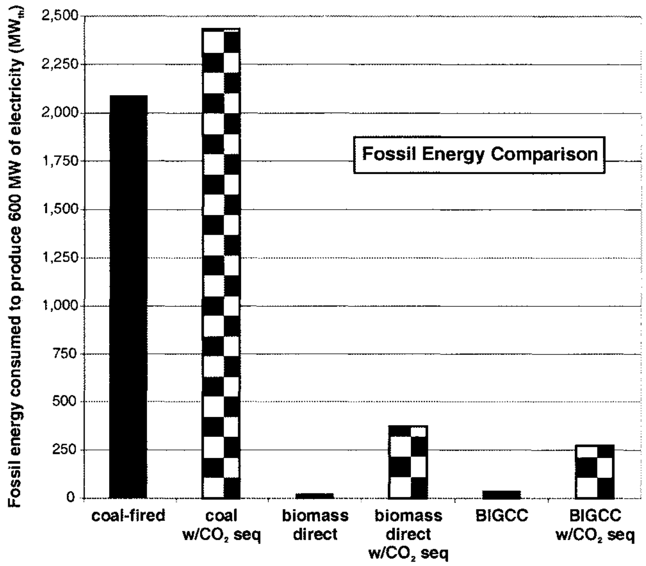

Figure 8. Comparing Fossil Energy Consumption

Cost of Electricity without CO_2 Sequestration

The cost of electricity generation is determined by several factors including, the power generation technology (e.g., coal-fired boiler, direct-fired biomass, etc.), the power plant size, and the feedstock cost. Currently, the cost to generate electricity from coal is about 2 - 3¢/kWh [7]. Biomass power via direct combustion can be generated for about 8 - 9¢/kWh [8] while advanced technologies using gasification combined-cycle are estimated to produce electricity for 5 - 6¢/kWh ([9] and [10]).

Costs Associated with CO_2 Sequestration

The cost of CO_2 sequestration consists of the cost to capture, compress, transport, and store the CO_2 from the power plant flue gas as well as the cost to produce additional electricity to make up for the lost generating capacity. Several studies by others have examined the cost of electricity from a coal-fired power plant with CO_2 sequestration. Table 3 summarizes the information from some of these studies. Only the cost to capture and compress the CO_2 is included in each analysis. These references have not incorporated CO_2 transport and storage costs into their analysis. However, a few of the studies did discuss these costs stating that they will be low compared to the cost of capture and compression. Additionally, the cost of replacement power to make up for the lost generating capacity needs to be included.

Table 3 shows that the cost of electricity from a coal-fired power plant with CO_2 sequestration is expected to increase by about 2.7¢/kWh (This is the average of the data in Table 3 excluding the cost given by reference [16]). Again, this number does not include the cost for storage and transport of the CO_2 and the cost of replacement power. These studies also show a wide range for the cost of CO_2

avoided; \$34 - 76/tonne of CO_2 avoided. Note that the cost per tonne of CO_2 avoided is not the same as the cost per tonne of CO_2 captured. Depending on the efficiency of the plant, for a coal-fired power plant the amount of CO_2 captured in terms of kg/kWh will be roughly 1.4 times the amount of CO_2 avoided. The kg of CO_2 avoided/kWh of electricity produced is less because there is a large energy penalty associated with capture and compression of the CO_2. The CO_2 avoided is the difference in the kg of CO_2 emitted/kWh of electricity produced for the reference plant compared to the plant with CO_2 sequestration.

Table 3. Coal-fired Plants with CO_2 Sequestration - Costs in the Literature

Reference	Electricity cost (¢/kWh)		Increase in electricity cost from base case		\$/tonne of avoided CO_2
	Base	With CO_2 seq	¢/kWh	%	
[2]	3.7¢	6.1¢	2.4¢	65%	\$34
[11]	3.7¢	6.4¢	2.7¢	73%	\$47
[12]	4.3¢	6.9¢	2.6¢	60%	\$40
[13]	5.2¢	8.7¢	3.5¢	70%	---
[14]	4.9¢	7.4¢	2.5¢	51%	\$37
[15]	3.7¢	6.4¢	2.7¢	73%	\$50
[16]	4.9¢	10.8¢	5.9¢	120%	\$76
[17]	4.2¢	7.0¢	2.8¢	67%	---

CO_2 Transport and Storage Costs

Several factors will affect the transport and storage cost of CO_2 including the amount of CO_2 transported, the transport distance, the storage option (land or ocean), the storage medium (gas field, oil field, or aquifer) and the depth of storage. Information on the cost to transport and store CO_2 was gathered from various literature sources and some of this information is given in Table 4. As can be seen from the data in this table, the cost differs significantly (\$1 - \$35/tonne of CO_2 avoided) depending on the size of the pipe, the transport distance, and the storage medium.

Table 4. Cost of CO_2 Transport and Storage from the Literature

Reference	Information from source	Calculated Cost (\$/tonne of CO_2 avoided)
[12]	\$5-15/Mg CO_2 avoided	\$5 - 15
[16]	\$0.54/100 scf of CO_2 for 100 mi	\$14
[18]	Pipeline costs = \$0.02/mile/ton	\$6
[19]	pipeline and disposal cost	\$4 - 7

Reference	Information from source	Calculated Cost ($/tonne of CO_2 avoided)
[20]	transport = $3-15/100km/tonne of avoided C underground storage = $2-20/tonne of avoided C	$5 - 35
[21]	Cost of CO_2 transport & injection	$10
[22]	0.5 m (20 in) dia pipeline @ 500 km (310 mi) with capacity of 18,000 tonne/day	$17
[23]	storage = $1-3/tonne of CO_2 transport for 100 km = $1-3/tonne of CO_2	$3 - 8
[24]	for 250 km: 16 inch pipe = $7/tonne of CO_2; 30 inch = $2.1/tonne of CO_2; 64 inch = $1/tonne of CO_2	$1 - $10
[25]	transport: Close proximity, costs would be solely compression: $7/tonne of CO_2 @ annual volume of 1 million tonnes. At 200 km (124 mi) distance: $11/tonne of CO_2 @ annual volume of 1 million tonnes and $18/tonne of CO_2 @ annual volume of 4 million tonnes. storage: $3/avoided tonne of CO_2 if 1 trap is need and $6-7 for 3 traps; $2 if 1 depleted gas field is needed to $5 for 3 depleted gas fields	$12 - 32

Cost of Electricity with CO_2 Sequestration

To get a true picture of the increase in the cost of electricity with CO_2 sequestration, data was taken from the studies listed in Table 3 and 4 and a total cost of electricity was calculated. The results are shown in Table 5. The cost of electricity from coal increases by 191% from 2.5¢/kWh to 7.3¢/kWh.

Table 5. Cost of electricity from coal including CO_2 sequestration

System	Cost of electricity (¢/kWh)				
	Prior to CO_2 sequestration	Cost of CO_2 capture & compression	Cost of CO_2 transport & storage	Cost of replacement power	Total cost
Coal-fired	2.5	2.8	0.9	1.1	7.3

Biomass power using an advanced gasification combined-cycle technology, BIGCC, is cheaper than the coal-fired system with CO_2 sequestration, about 5.5¢/kWh compared to 7.3¢/kWh, and the BIGCC system uses a dedicated feedstock resulting in a nearly carbon neutral system (see Figure 5). The cost of electricity from a direct-fired biomass system is slightly higher than the coal-fired system with CO_2 sequestration, about 8.5¢/kWh compared to 7.3¢/kWh. However, an additional 1¢/kWh increase in the price of electricity from the coal-fired system with CO_2 sequestration will make the direct-fired biomass system cost competitive. With the wide range of costs given in Table 3 and 4 this is highly likely.

Cost of Avoided Greenhouse Gas Emissions for the Biomass Systems

The cost of electricity along with the price of avoided GHG emissions required to make the biomass systems competitive to the coal-fired system with and without CO_2 sequestration are shown in Figure 9. For example, the difference in the electricity price for the direct-fired biomass system (Case 2) compared to the coal-fired system (Case 1) is 6.0¢/kWh. When comparing the GHG emissions from these two systems along with the difference in the cost of electricity, an emissions credit of $48/tonne of CO_2-equivalence will make the biomass direct system competitive to the coal system. However, when comparing the direct-fired biomass system to coal with CO_2 sequestration (Case 1A), this number drops to $19/tonne of CO_2-equivalent emissions. The BIGCC system (Case 3) is already cheaper than the coal-fired system with CO_2 sequestration (Case 1A) and the greenhouse gas emissions are less (1.3 compared to 0.3 million tonnes CO_2-eq/yr. See Figure 7.). Comparing the electricity costs and GHG emissions for BIGCC (Case 3) to coal without CO_2 sequestration (Case 1) requires an emissions credit of $44/tonne of CO_2-equivalent emissions to make the biomass system cost competitive. Even though the difference in the cost of electricity is less between the BIGCC system (Case 3) and the coal-fired system (Case 1) than between the direct-fired biomass system (Case 2) and the coal-fired system (Case 1), the amount of GHGs emitted is lowest for the direct-fired biomass system. This is due to the avoided emissions from using biomass residue.

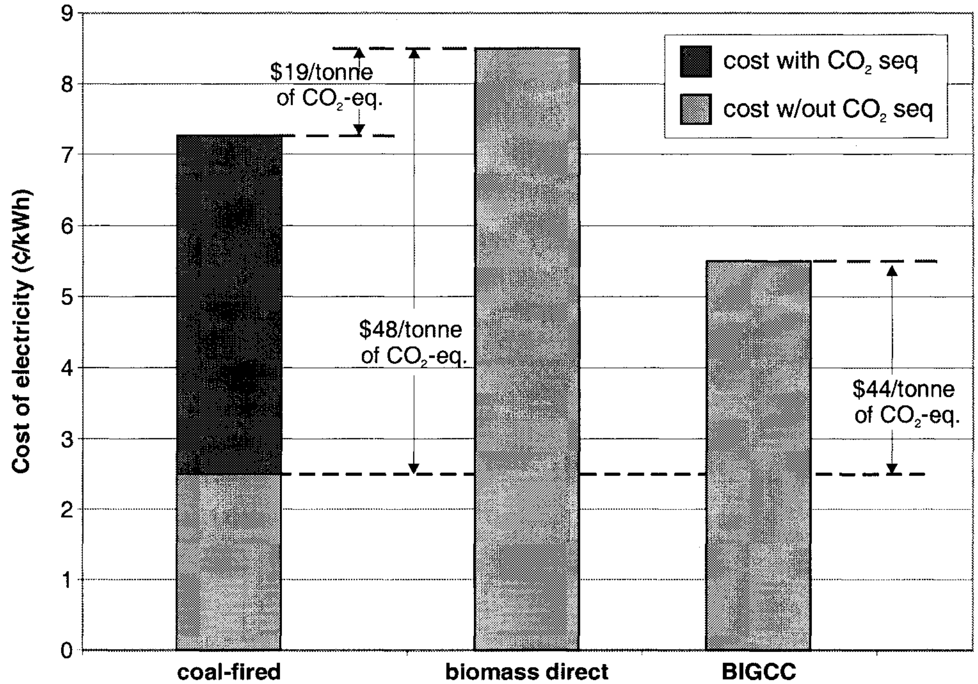

Figure 9. Cost of Electricity and Required Emissions Credit

Conclusions

This analysis shows how important it is to take a life cycle approach and include the upstream process steps in order to get the true environmental picture of electricity generation and the effect of CO_2 sequestration. Substituting electricity generated by coal with biomass electricity will substantially reduce the GWP along with significantly decreasing the fossil energy consumption per kWh of electricity generated. Even with CO_2 sequestration, the amount of GHG emissions per kWh of electricity produced is more for the coal-fired system than for the biomass power generation systems.

Furthermore, when examining the cost of electricity with CO_2 sequestration it is important to include the cost to capture, compress, transport, and store the CO_2 as well as the cost to produce additional electricity to make up for lost generating capacity. In doing so, biomass power from an advanced combined-cycle system is less than the cost of electricity from a coal-fired power generation system with CO_2 sequestration and biomass power from a direct-fired system requires only a small GHG credit to make the system cost competitive. Therefore, the use of biomass for power production can be a cost effective solution in helping to reducing GHG emissions as well as reducing fossil energy consumption from electricity generation. These biomass technologies also avoid the concern about the fate of sequestered CO_2 and its long-term environmental effects.

References

1. Spath, P.L; Mann, M.K. 2000. *Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System.* National Renewable Energy Laboratory, Golden, CO, TP-570-27715.

2. Hendriks, C. 1994. *Carbon Dioxide Removal from Coal-Fired Power Plants.* Kluwer Academic Publishers. Dordrecht, Netherlands.

3. Spath, P.L; Mann, M.K. 1999. *Life Cycle Assessment of Coal-fired Power Production.* National Renewable Energy Laboratory, Golden, CO, TP-570-25119.

4. Mann, M.K.; Spath, P.L. 2000. "A Comparison of the Environmental Consequences of Power from Biomass, Coal, and Natural Gas." *First World Conference and Exhibition on Biomass for Energy and Industry.* June 5-9, Seville, Spain.

5. Mann, M.K.; Spath, P.L. 2001. "A Life Cycle Assessment of Biomass Cofiring in a Coal-Fired Power Plant." *Clean Products and Processes*, Vol. 3, Issue 2, pp. 81-91.

6. Mann, M.K.; Spath, P.L. 1997. *Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System.* National Renewable Energy Laboratory, Golden, CO, TP-430-23076.

7. U.S. Department of Energy. 1998. *Competitive Electricity Prices: An Update.* Energy Information Administration, Office of Integrated Analysis and Forecasting. Washington, D.C.

8. U.S. Department of Energy. 1997. *Renewable Energy Technology Characterizations.* Office of Utility Technologies, Energy Efficiency and Renewable Energy. Washington, D.C. TR-109496.

9. Craig, K.R; Mann, M.K. 1996. *Cost and Performance Analysis of Biomass-Based Integrated Gasification Combined-Cycle (BIGCC) Power Systems.* National Renewable Energy Laboratory, Golden, CO, TP-430-21657.

10. Overend, R.P.; Bain, R.L. 1995. "Technical Support of the U.S. DOE Biomass Power Program in the Development of Biomass to Electricity Technologies." American Chemical Society Division of Fuel Chemistry: Preprints of Papers Presented at the 210th American Chemical Society National Meeting, 20-25 August 1995, Chicago, Illinois. Vol. 40(3), 1995; pp. 654-657. Acc No. 16649.

11. Audus, H. 2000. "Leading Options for the Capture of CO_2 at Power Stations." Fifth International Conference on Greenhouse Gas Control Technologies (GHGT-5). August 13-16. Cairns, Australia.

12. Herzog, H.J. 2000. "The Economics of CO_2 Separation and Capture." *Technology*; Vol. 7S, pp. 13-23.

13. Holt, N.; Booras, G. 2000. "Analysis of Innovative Fossil Fuel Cycle Incorporating CO_2 Removal." *2000 Gasification Technologies Conference Proceedings*. October 8-11, San Francisco, California.

14. IEA Greenhouse Gas R&D Programme. 2000. Carbon Dioxide Capture From Power Stations. ISBN 1 898373 15 9.

15. IEA Greenhouse Gas R&D Programme. 2000. *Leading Options for the Capture of CO_2 Emission at Power Stations*. Report Number PH3/14.

16. Johnson, H.E.; Vejtasa, S.A.; Pelline, J.E.; Biasca, F.E.; Simbeck, D.R.; Dickenson, R.L. 1992. Screening Analysis of CO_2 Utilization and Fixation. Prepared for U.S. DOE under contract number DE-AC01-88FE61680 (Task 20).

17. Simbeck, D. 1999. "A Portfolio Selection Approach for Power Plant CO_2 Capture,Separation and R&D Options." Greenhouse Gas Control Technologies. Elsevier Science Ltd.

18. Bergman, P.D.; Winter, E.M.; Chen, Z. 1997. "Disposal of Power Plant CO_2 in Depleted Oil and Gas Reservoirs in Texas." *Energy Conversion Management*, Vol. 38, Supplement, pp. S211-s216.

19. Smelser, S.C.; Booras, G.S. 1991. *An Engineering and Economic Evaluation for CO_2 Removal from Fossil Fuel-Fired Power Plants*. Flour Daniel, Irvine, California. EPRI IE-7365.

20. Blok, K.; Williams, R.H.; Katofsky, R.E.; Hendriks, C.A. 1997. "Hydrogen Production from Natural Gas Sequestration of Recovered CO_2 in Depleted Gas Wells and Enhanced Natural Gas Recovery." *Energy*, Volume 22. Number 2/3. pp. 161-168.

21. David, J; Herzog, H. 2000. "The Cost of Carbon Capture." Fifth International Conference on Greenhouse Gas Control Technologies. August 13-16, 2000.

22. IEA Greenhouse Gas Program R&D. 1999. *Ocean Storage of CO_2*. ISBN 1 898373 25 6.

23. IEA Greenhouse Gas R&D Programme. 2001. *Putting Carbon Back in the Ground*. ISBN 1 898373 28 0.

24. Skovholt, O. 1993. "CO_2 Transportation System." *Energy Conversion Management*, Vol. 34, No. 9-11, pp. 1095-1103.

25. Wildenborg, T. 2000. *Costs of CO_2 Sequestration by Underground Storage*. Greenhouse Issues, No. 47.