Greenhouse Gas Emissions from Coal Gasification Power Generation Systems[@]

by

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Abstract

Life cycle assessments (LCA) of coal gasification-based electricity generation technologies for emissions of greenhouse gases (GHG), principally CO_2, are computed. Two approaches for computing LCAs are compared for construction and operation of integrated coal gasification combined cycle (IGCC) plants: a traditional process-based approach, and one based on economic input-output analysis named Economic Input-Output Life Cycle Assessment (EIO-LCA). It is shown that EIO-LCA provides a more complete accounting for emissions incurred during construction resulting in larger estimates of emissions. For plant construction process-based LCA computes emissions that approximate a subset of emissions computed via the EIO-LCA method. For plant operation, however, only emissions due to mining and consumption of coal at the plant are significant, and both methods of analysis give essentially equivalent results. For conventional coal-based power generators, and even for those that would capture 90% of carbon emissions, GHG emissions during a typical operating life of 30-50 years dominate the life cycle. Literature values for life cycle emissions of GHGs for a number of renewable technologies are compared to emissions from IGCC systems with and without carbon capture and from natural gas combined cycle (NGCC) without capture. Lowest life cycle emissions are achieved with dammed hydro power and wind farms. IGCC with 90% CO_2 capture exhibits lower life cycle GHG emissions than NGCC and solar photovoltaic systems.

Keywords: Gasification, Life-cycle Assessment, Greenhouse Gases, IGCC

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Introduction

Life cycle assessment is a good approach for ranking environmental performance of technologies being considered for new equipment installations, as it considers environmental impacts over the expected lifetime of an installation. LCA, therefore, can aid in making technology selection decisions for new installations and in guiding environmental policy by governments. A long term point of view has long been accepted in the business world for ranking profitability of competing investment opportunities, where concepts such as discounted cash flow, present value, and (for the electricity generation sector) levelized cost of electricity have been used to estimate profitability over the expected lifetime of a potential investment. The concept of LCA also uses a project lifetime perspective to consider resource requirements and waste product generation for alternative technologies that could be used to provide a product or service over a specified period. The LCA approach has been used to compare lifetime resource requirements and noxious emissions of a large number of individual compounds and classes of compounds discharged to the atmosphere, to waterways, and to the land. However, with so much data available, researchers are faced with the following questions: how to choose which emissions or resources to subject to detailed analysis for LCA, and how to compare LCA performance for different classes of emissions.

In the present paper, LCAs are performed on coal-gasification based electricity generators with and without the capability to capture carbon dioxide, the principal greenhouse gas. The paper treats only estimation of life cycle GHG emissions; it does not consider environmental impact analysis. Different radiative absorbers (CO_2, methane, N_2O, and CFCs) are put on a common basis by use of Global Warming Potentials (GWP) using a 100-year time horizon as is done by Intergovernmental Panel on Climate Change (*Houghton et al. 1995, Houghton and Ding 2001*). For generators that would capture CO_2, the collected gas would be stored deep in the earth or deep at sea so as to keep it out of the atmosphere, reducing air emission of GHGs. The exclusive focus on GHGs is for the following reasons. Of all emissions from coal-fired plants, including acid gases, particulate matter, heavy metals, and GHGs, the emission class that is proving most difficult to limit is GHGs. Indeed, in 1999, CO_2 emissions from coal-fired generators represented 29% of total U.S. CO_2 emissions, and the U.S. was responsible for 25% of global CO_2

emissions (*Energy Information Administration 2000a, 2002a*). The Energy Information Agency (*2000b*) projects that total CO_2 emissions from coal-fired generators will continue to grow, although CO_2 emission rate, kg/kWh, may decrease due to efficiency improvement. By contrast, sulfur and NOx emissions from coal-fired generators have been reduced in recent years even as their electrical output has increased (*Energy Information Administration 2000a*). The second reason is that of all coal-based emissions, CO_2 is the hardest to control by adding retrofit technology after a generator has been built and put into operation. While retrofit technologies for CO_2 capture are the subject of research, to the present time they appear to be substantially more expensive and to carry a higher energy penalty than if provision for capture were designed into the process (*Simbeck and McDonald 2000*). Thus the class of life cycle emissions for coal-based power generators that is most important to evaluate for new plant installations is often GHGs.

Two approaches have been developed by researchers for conducting environmental LCAs. The better known approach is process oriented and has been the attention of much work by USEPA (*Vigon, et al. 1993*) and the Society for Environmental Toxicology and Chemistry (*SETAC 1993, SETAC 1998*). The newer approach is an extension of economic input-output analysis to the physical realm. This extension has been developed in the U.S. by researchers at Carnegie Mellon University (CMU) (*Carnegie Mellon University 2002, Hendrickson et al. 1998*). Parallel developments have occurred elsewhere in the world (*Voorspools et al. 2000, Lenzen 2001, Suh 2001*). CMU maintains a web enabled input-output model of the U.S. economy by a method named EIO-LCA, and this model has been used in the present work (*CMU 2002*). Both approaches to LCA evaluate emissions for plant construction and operation separately; then the two components are summed to project lifetime emissions. Demolition at the end of service life can be handled similarly, but for fossil power generating plants, related emissions are thought to be a small fraction of the plant construction and operation (*Lenzen 2001, Gorokhov et al. 2002*).

Comparisons of the two methods for doing LCA have been presented in the literature (*Hendrickson et al. 1998, Voorspools et al. 2000*). In brief, the process-based LCA develops estimates of emissions in the course of building a plant by determination of energy use and the ***masses*** of major materials used in the plant, such as steel, copper, aluminum, and concrete, together with estimates of emissions per unit mass for converting the construction materials from base ores, fashioning them into products, and installing them in a plant. By contrast, the input-output method tracks the ***money*** spent for various sections of a plant. The economic input-output approach considers implications for resource requirements and waste emissions across the entire economic "supply chain" for producing a particular good or service (e.g. building a power plant and generating electricity). The EIO-LCA web model categorizes expenditures in nearly 500 economic sectors defined by the U.S. Department of Commerce (DOC). Researchers at CMU have developed estimates of the emissions of the four principle GHGs (and many other environmental measures) for dollar-denominated activity in each sector of the U.S. economy.

The input-output approach to LCA is "top down" in the sense that input data to such models are capital and operating costs for the entire plant. Process-based LCA is "bottom up" in the sense that the subjects of analysis are individual processing units and the flow rate and composition of streams entering and exiting such units. The different philosophies for computing emissions via the process-based and input-output approaches extend to the operation phase. The process-based approach calculates emissions due to consumption of the main feedstocks to the plant. The input-output approach identifies operating costs, categorizes them according to economic sector, and computes emissions associated with the dollar value expended in each economic sector. .

In this paper EIO-LCA is used to compute life cycle emissions of GHGs for an integrated gasification combined cycle plant (without CO_2 capture), and the results are compared to a previously performed process-based LCA for a similar plant. Then EIO-LCA is used again to analyze an IGCC plant that would employ nominal 90% capture of CO_2. The results are compared to a published study of life cycle GHG emissions for electrical generators that employ several renewable energy technologies.

Results

Process-based LCA for an IGCC plant without CO_2 capture

Researchers at the National Energy Technology Laboratory (NETL) prepared process-based LCAs for IGCC plants (*Gorokhov et al. 2002*). Amounts of a large number of substances that were used in plant construction, consumed in plant operation, and generated as waste products during plant operation were estimated: 56 process inputs, 25 "products," 43 airborne residuals, 9 liquid-borne residuals, and 20 solid-borne residuals. We present below some of their results for the IGCC plant with a nameplate capacity of 381 MW. It was designed for use with Illinois No. 6 bituminous coal and had a net efficiency of 39.6% (higher heating value, HHV). The NETL study (using the SETAC approach) included estimates of emissions of three principal GHGs: CO_2, methane, and nitrous oxide. Table 1 shows the emissions of methane and nitrous oxide as equivalent amounts of CO_2 for radiative forcing, using mass-based Global Warming Potentials for these gases of 21 for methane and 310 for nitrous oxide (*Houghton et al. 1995*). More recent data give GWP values of 23 for methane and 296 for nitrous oxide *(Houghton and Ding 2001).* As will be seen, in the work presented here CO_2 is by far the dominant GHG, so differences in the GWP for methane and nitrous oxide have negligible effect. In Table 1 the column labeled "Total GWP" represents the sum of the radiative forcing by all three GHGs.

A number of features in Table 1 are worth noting. One is that for all three kinds of activity shown, the dominant GHG is CO_2, which contributes over 10 times as much to GWP as do the other GHGs. Also, demolition was estimated to release only about 1/8 as much GWP as construction. And finally, the annual operation of the plant would release about 40 times more GWP than construction. Thus, in the course of the complete life cycle of a plant, assumed 30 years in this study, the contribution to GWP by construction and demolition would be negligible compared to emissions from operation.

The specific carbon emission[*] during operation of a fossil-fueled power plant is governed by generation efficiency. The specific carbon emission for the plant described in Table 1, expressed as equivalent mass of CO_2, labeled CO_2 e, is calculated to be 0.791 $MtCO_2$ e/MWh, where Mt is metric ton.

[*] Specific carbon emission is defined as mass of CO_2 (e.g. Mt) divided by a unit of electricity generation (e.g.. MWh)

Economic input-output based LCA for construction of an IGCC plant without CO_2 capture

Economic input-output analysis is a technique that permits the estimation of the effect of activity in any sector of the economy on any and all other sectors of the economy. The U.S. DOC collects and processes the information needed to describe the U.S. economy in terms of nearly 500 sectors. The interdependence of some economic sectors is intuitive-- for instance, the dependence of electricity-intensive manufacturing sectors on the coal mining sector due to the use of electricity generated using coal. Most interdependencies are less obvious. For example, construction sectors have small but finite dependence on sectors dealing with restaurants and automotive services.

The total resource requirements for, or emissions from, a sector include a contribution from the sector itself. This latter contribution describes the final step where the product or service is produced. This self-referencing entry is called the "direct" contribution. The "direct" contribution to GWP (e.g. from burning fossil fuels) can represent a widely varying fraction of the total GWP, depending on which economic sector is considered. For the electricity generation (utilities) sector, direct contribution represents more than 98% of total GWP emissions, as GWP emissions from power plants dominate. For the sector, "Engineering, architectural, and surveying services," direct contribution represents less than 8% of the total, as emissions from support activities in the supply chain dominate. The contribution to GWP from every economic sector for any particular economic activity is provided by the EIO-LCA model (*CMU 2002*).

For computing LCA, proponents of the input-output approach say that compared to process-based LCA, the former method includes items that the latter misses. The overlooked contributions are of two sources. One can be thought of as due to limited "horizontal reach" in the process-based LCA approach. This would include small, non obvious activities like transportation of workers and materials, and restaurants serving construction projects, for instance. The other kind can be explained by insufficient "vertical reach" with process-based LCA. Process-based LCA would typically compute emissions associated with manufacture of cement used in a construction project of interest, but it would not usually compute the prorated share of emissions due to the construction of the plant that made the cement. Thus process-based LCA unavoidably involves an arbitrary cut-off point as to which activities are counted and which are not. By contrast the economic input-output method of LCA is inclusive of all activities that contribute to the project of interest (*Hendrickson et al. 1998*).

The CMU web site for EIO-LCA presents emissions data for GHG gases CO_2, methane, nitrous oxide, and CFCs. For each gas other than CO_2, global warming burden is presented as $MtCO_2e$ for a given dollar value of activity in a particular economic sector, using the same set of GWPs as was used in Table 1.

The DOC revises their input-output tables describing the U.S. economy at roughly five year intervals. With the CMU web site it is possible to use input-output table values based on 1992 or 1997 data that divide the economy into nearly 500 sectors. In the present work we have used data from 1997 annual tables, which are expressed in 1997 dollars. Where prices were given in dollars of another year, the implicit price deflator for GDP computed by the DOC has been used to correct for inflation (*Bureau of Economic Analysis 2003b*).

The plant that is the subject of EIO-LCA in the present work was described in an engineering feasibility study conducted by Buchanan et al. *(1998*). The plant has nameplate capacity of 543 MW with a heat rate for the plant of 8522 Btu/kWh, equivalent to a conversion efficiency of 40.0%, both on HHV basis. Similar to the 381 MW plant, the 543 MW plant is designed for use with Illinois No. 6 coal. A feature of the EIO-LCA method is that it employs average values for economic parameters computed over the entire data base. Thus, for example, the calorific value of coal and the methane emissions in the mining of the coal represent averages for the U.S. economy. As will be seen, the EIO-LCA analysis of the 543 MW plant will assume use of coal of average composition of that mined in the U.S. in 1997 instead of Illinois No. 6. There are advantages and disadvantages to this averaging process, but it is an unavoidable feature of use of EIO-LCA.

The earlier NETL study of IGCC power system emissions (*Gorokhov et al. 2002)* considered two plants with different kinds of gasifiers. It was found that only plant efficiency and plant capacity materially affected GHG emissions. The same approach is applied here, and results are normalized per MW of plant output.

Total plant cost is estimated as $674 million (1998 dollars) for the 543 MW plant (*Buchanan et al. 1998*). Estimated cost for the 543 MW plant is broken into 14 plant sections by Buchanan et al. For each plant section cost estimates are given for each of the following components.

- Equipment
- Material
- Installation labor
- Engineering Contract Management, Home Office & Fee
- Process contingency
- Project contingency

The sum of costs for all six components for all 14 plant sections yields the total plant cost.

The EIO-LCA method requires use of cost expended in particular economic sectors to compute emissions. Therefore the presentation of costs is rearranged as follows. Equipment cost was used for 13 of the 14 plant sections. (One plant section, "Buildings & Structures," did not have equipment costs.) Three additional cost categories were introduced to account for the other five components listed above. Titles for the new categories were "Equipment Installation," "Engineering Contract Management, Home Office & Fee," and "Contingencies." The cost attributed to "Equipment Installation" was the sum of all Material and Installation labor costs given in the original breakout. The cost for "Contingencies" was the sum of all Process and Project contingency costs in the original breakout. The category "Engineering Contract Management, Home Office & Fee" contained the sum of all costs of this type recorded for the 14 original plant sections.

Thus there were now 16 cost categories each with one associated cost, the sum of which again was total plant cost. For each cost category the DOC I-O sector that best described the category was chosen, and the GHG emissions recorded. This classification of costs is shown in Table 2. Names of economic sectors used, and their 6-digit DOC identifiers for the I-O tables, are given.

The EIO-LCA tables are based on producer prices, while the costs given by Buchanan et al. are purchaser prices. Purchaser prices were converted to producer prices as inputs into the EIO-LCA model using the 2-digit Standard Industrial Classification sector level information on relative purchaser and producer costs in Kuhbach and Planting (*2001*) and BEA (*2003a*). To be consistent with the CMU EIO-LCA database, online data from the BEA's *1997 Annual IO Tables* were used. From the BEA website, the user may construct a one-column table with the 2-digit commodity sectors as rows and the industry (electricity) as the column. Extracting these data from "The Use of Commodities by Industries before Redefinitions" table yields, in dollars, the amount of the commodity used by electric suppliers in 1997. The website shows these amounts initially in producer prices, and then adds columns showing transport prices, wholesale and retail margins and purchaser prices. Since purchaser prices equal producer prices plus transport plus margins, the adjustment factor may be calculated. Table 2 shows costs, adjustment factors, and computed producer prices by economic sector. It is observed that for economic sectors for which value added is primarily due to labor, the ratio of purchaser to producer price is unity or close to unity.

Results of the EIO-LCA for plant construction are shown in Table 3. Similar to the results with the process-based LCA, methane contributes about 10% to the total GWP, and the other GHGs make a much smaller contribution.

Input-output based LCA for operation of an IGCC plant without CO_2 capture

New users of EIO-LCA might think it should be possible to compute emissions from operation of coal-fired generators by directly accessing the sector in EIO-LCA for power generation. The economic sector is named "Power: Electric services (utilities)," and it has a listing of resource requirements and emissions. The data presented are averages for all power generators in the country, however, including those employing hydro, nuclear, natural gas, as well as coal. Thus another approach is required to calculate GHG emissions from the 543 MW IGCC plant of interest by use of EIO-LCA.

A good place to start to get the information needed is in the design report for the plant, where the plant heat rate (Btu/net kWh) and components of the calculated Cost of Electricity (COE) are given (*Buchanan et al., 1998*). An estimate of COE expressed both for a full year's operation and per net kWh is broken out in the following components:

- fixed and variable operations and maintenance (O&M)
- consumable operating cost (less fuel)
- fuel
- capital service

Capital service is effectively a deferred charge for plant construction, so it is not included in computation of emissions during operation. To assign the remaining production costs to the appropriate economic categories, we consider the generating plant to consist of two essential aspects. One aspect consists of all operations involved in mining and transporting coal to the plant, then converting it to electricity, with the attendant emissions to the atmosphere for each of these operations. The other aspect consists of a maintenance and repair function needed to keep the plant in operation.

To estimate emissions due to maintenance and repair, components of COE due to fixed and variable O&M and to consumable operating costs (less fuel) are summed. To use EIO-LCA, these costs are ascribed to the I-O category "Other maintenance and repair construction," DOC Sector 230340. With an assumed plant capacity factor of 0.85, Buchanan et al. (*1998*) report operating costs for the summed categories of $23.7 million (1998 dollars), which is equivalent to 0.58 cents/kWh. Data provided by the Bureau of Economic Analysis of the DOC indicate that for economic sectors that describe both repair services and professional services, the producer price and purchaser price are the same *(Bureau of Economic Analysis, 2003a)*.

Therefore, the sum of \$23.7 million, adjusted by the GDP Deflator to \$23.4 million (1997 dollars) is used in Table 4 to compute GHG emissions due to the repair and maintenance of the plant.

With respect to GHG emissions due to mining, transportation, and consumption of coal at the plant, it is again necessary to take account of the fact that data contained in EIO-LCA represent national averages. Buchanan et al. (*1998*) designed the 543 MW IGCC plant for use with a particular coal, Illinois No. 6. The fuel cost component of COE given by Buchanan et al. is a delivered cost for that coal to a mid west plant site. By contrast, data for coal in EIO-LCA are for average prices, average thermal contents, and average methane emissions incurred due to mining. To use EIO-LCA to estimate GHG emissions due to mining, transportation, and combustion, we assume that the plant heat rate given by Buchanan et al. (1998), 8522 Btu/kWh (HHV), is constant independent of the thermal content of the coal. At 0.85 capacity factor, the total heat load for the plant is 34.5 E+12 Btu/y. EIO-LCA is used to compute emissions associated with this amount of coal.

The approximate average heat content of two categories of coal mined in 1997 was as follows (*Energy Information Administration 2002b)*:

- Production: 21.296 million Btu/short ton
- Consumption by electric power sector: 20.518 million Btu/short ton

The difference between these two values of heat content is one illustration of the limit of accuracy possible using EIO-LCA. For purposes of computing methane emissions from mining, the value for “Production” should be used. For computing carbon dioxide emissions due to combustion at the plant, the value for “Consumption by electric power sector” should be used. Here we have used an average value, 20.9 million Btu/short ton.

To compute carbon dioxide emissions at the plant due to coal combustion, the average carbon content of the coal is also needed. In 1997 average coal consumed by electric power producers contained 25.91 metric ton carbon per billion Btu (*Energy Information Agency 2001)*. These values of heat content and carbon content were used to calculate carbon dioxide emissions due to coal combustion shown in Table 4.

Thus to supply the 34.5 E+12 Btu required for one year's operation, 1.65 million short tons of average coal is required, which contains 0.894 million Mt carbon. For the present analysis we neglect the small amount of unburned carbon that would exit the gasifier, so all carbon fed to the plant is assumed to be converted to CO_2. The GHG nitrous oxide is formed in measurable amounts in some relatively low temperature coal combustion systems, such as fluidized beds. In an IGCC system, however, the synthesis gas formed in the gasifier is combusted at a relatively high temperature, typically 1200 degrees C or higher, and N_2O formation is negligible (*Battelle, 1997*).

To use EIO-LCA to compute GHG emissions due to mining and transportation of coal it is necessary to know the average cost of coal to electric utilities in 1997. The average delivered price of coal to electric utilities that year was $18.14/short ton *(Energy Information Administration, 2002c).* BEA data indicate that the purchaser-to-producer coal price ratio is 1.45, and that transport, primarily rail, represents 30.3% of the purchaser price. Thus, of the average $18.14 delivered price, $12.51 may be allocated to coal mining (producers) and $5.50 to rail transport (with a small rounding error noted). The dollar values in each category are used with the appropriate economic sector in EIO-LCA to compute GHG emissions from mining and for transportation. DOC Sector 70000, "Coal," is used for mining, and Sector 650100, "Railroads and related services" is used for transportation. Thus for the computation of emissions during operation that are shown in Table 4, $21.0 million are used for producer cost of coal, and $9.20 million for rail transportation.

Table 4 shows that about 98% of the GWP from operation is due to CO_2 emissions with the bulk of the remainder due to CH_4. Most of the methane emissions result from mining, for which CH_4 makes a larger contribution than CO_2 to GWP. For higher rank, gassier coals than the "average coal" assumed for EIO-LCA the methane contribution to GHG could be somewhat larger, but it would not exceed about 5% of the GWP due to combustion of the coal. The Table also shows that consumption of coal at the power plant is responsible for about 96% of total GWP, with the bulk of the remainder due to mining. Computation of GWP for plant operation by a process-based approach to LCA would give results very close to those developed using EIO-LCA. The small differences that would be observed would be due to use of data for a specific coal and perhaps specific transportation mode and distance in the process-based approach instead of national averages as is done with EIO-LCA.

Input-output-based LCA for IGCC plant with CO_2 capture

For the two IGCC plants considered above, which did not employ CO_2 capture, GWP from operations over their expected lifetimes was much larger than GWP from construction. We now consider an IGCC plant that employs nominal 90% CO_2 capture. The technical features of such plants have been described (*EPRI 2000, Schoff et al. 2002*). The cited reports explain why CO_2 capture can be conducted more economically with IGCC power plants than with pulverized coal or natural gas combined cycle plants. The key is the relative ease of separating CO_2 from synthesis gas, where it is at relatively high concentration and pressure. For the plant that is analyzed, Schoff et al. assume that captured CO_2 leaves the plant as a liquid compressed to 1200 psig (8.38 MPa) at pipeline specification of purity.

The plant to be considered is Case 3E in a series of design studies performed by Schoff et al. (*2002*). Its nameplate capacity rating is 386 MW. It operates at net efficiency of 35.4% (HHV), which is equivalent to a heat rate of 9640 Btu/kWh. Its specific carbon emission is 0.077 $kgCO_2$/kWh when operated on Illinois No. 6 coal. The total plant cost is $584 million or $1510/kW (1999 dollars).

Some of the foregoing results are used to provide short cuts to computing GHG emissions for construction and annual operation by the EIO-LCA method. It is assumed that for construction, the value of Total GWP for the 543 MW plant can be divided by the total plant cost to yield a GWP intensity for plant construction, $MtCO_2e/\$10^3$, that applies equally to the plant providing for CO_2 capture. It is further assumed that the average ratio of purchaser price to producer price is the same for the two plants, so that purchaser prices for the two plants, when expressed in dollars of the same year, can be used to estimate GWP. The GWP intensity for construction of the 543 MW plant was 0.41 $MtCO_2e/\$10^3$ in 1999 dollars. Then the estimated GWP for construction of the 386 MW plant that provides for CO_2 capture is 24 E+4 $MtCO_2e$.

To estimate GWP for annual operation of the plant employing capture, use is made of the observation from Table 4 that only coal mining and coal consumption need to be considered. Emission of GHG due to mining is proportional to the amount of coal consumed by the plant. By use of the data for emissions due to coal mining shown in Table 4, and the respective heat rates for the two plants, the GWP due to mining for the 386 MW plant is 70300 MtCO_2e when calculated for 85% capacity factor, the same value as used in Table 4. This amount of GWP is equivalent to 0.024 kgCO_2e/kWh. Schoff et al. (*2000*) gave expected emissions of CO_2 due to plant operation with Illinois No. 6 coal, but we use values in Table 4 to estimate the emissions with the "average coal" used in the analysis of the 543 MW plant. The result is 0.091 kgCO_2e/kWh. See Table 5.

The combined GWP for mining and plant operation for the 343 MW plant employing capture is 0.115 kgCO_2e/kWh. Because only about 10% of CO_2 produced in coal combustion goes to the atmosphere for this plant, GHG emissions from coal mining are relatively more significant than for conventional coal-based generators without capture. In the present case, GWP emissions from coal mining are equivalent to about 21% of total GWP for plant operation. Table 5 also shows that when 90% CO_2 capture is practiced, GHG emissions for plant construction and one year's operation are of comparable size. This is in contrast to the findings for IGCC plants that do not practice capture, where GHG emissions from annual operations were much larger than for construction.

Discussion of Results

Comparisons are made of various methods and computed results for estimating life cycle GHG emissions for electric generating plants.

Comparison between Process-based and EIO-LCA methods of LCA for plant construction

Table 1 lists the Total GWP for construction of a 381 MW IGCC plant as 4.4E+04 MtCO_2e as computed by a process-based LCA. Table 3 lists values of Direct GWP and Total GWP for a similar but larger plant, 543 MW, as computed by the EIO-LCA. Both tables also show GWP normalized by plant size, i.e., GWP/MW. Comparison of normalized values of Total GWP in the two tables shows that the value of Total GWP for plant construction computed by the EIO-LCA method (520 MtCO_2e/MW) is about 5 times larger than that computed by the process-based method (115 MtCO_2e/MW). Note, however, that Total GWP/MW computed by the process-based method is 2-3 times larger than Direct GWP/MW (46 MtCO_2e/MW) as computed by the EIO-LCA method. An explanation for the observed difference in values of Total GWP/MW computed by the two methods is apparent. It appears that the process-based LCA method incorporates emissions arising from the final step in manufacture of equipment and materials used in plant construction, plus a portion of indirect emissions of roughly equal magnitude. Table 3 shows that indirect emissions are more nearly ten times larger than direct emissions, however, so the process-based LCA substantially underestimates the total.

A study performed for the International Energy Agency Greenhouse Gas R&D Programme developed estimates of cost and life cycle emissions of CO_2 for a 500 MW IGCC plant that captured and sequestered 83% of CO_2 emissions (*Berry et al. 1994*). A process-based approach was used for computing CO_2 emission during plant construction, which was estimated as 3.6 E+04 MtCO_2e, equivalent to 72 MtCO_2e/MW. This number compares to the value for Total GWP/MW estimated in the present study using EIO-LCA of 520 MtCO_2e/MW, which is about seven times larger. Thus, similar to the comparison of IGCC systems without CO_2 capture, for systems that include capture the economic input-output method yields substantially higher estimates for GHG emissions during construction.

Voorspools et al. (*2002*) compared estimates of life cycle GWP for nuclear power plants computed by both process-based and economic input-output methods and found that the latter estimates were 2-3 times larger. They declined to use economic input-output LCA to estimate life cycle GWP for solar photovoltaic and wind farm power systems because they said known sources of errors would invalidate the results. They pointed out that specialized equipment used in each of the latter two power systems were included in economic sectors that poorly represented them. The problem was magnified by the relatively small number of sectors used to describe the Belgian economy in their I-O model, just 64. Additionally, the economic data were over 16 years old. All of these issues appear to be much less serious in the application of the economic input-output LCA to fossil-based power systems in the U.S. by use of CMU's EIO-LCA.

Comparison of life cycle GWPs for electricity generators employing fossil energy or renewable technologies

As noted earlier, LCA appears to be useful in estimating life cycle emissions of GHGs for energy policy making. To use LCA in this way it is necessary to develop life cycle estimates of GWP emissions for many technologies, both fossil energy based and renewable, all on a consistent basis. Pacca and Horvath (*2002)* have recently made a notable contribution in this area by considering an upgrade to the generating capacity of the Glen Canyon hydroelectric plant on the Colorado River. These authors estimated the GWP for construction of the entire Glen Canyon hydroelectric plant and reported that in 1999 the power plant generated 5.55 TWh, which became a key parameter in a comparative study of a number of generating technologies. They estimated plant size (land area requirements and nameplate capacities), and GWP emissions for construction and for 20 years' operation at an output matching that of Glen Canyon Dam, i.e., 5.55 TWh/y, for the following technologies:

- Solar photovoltaic
- Wind farm
- Coal-fired generator
- Natural gas combined cycle

Pacca and Horvath *(2002)* estimated reasonable capacity factors for each technology they considered. For fossil fuel-based technologies the capacity factor was 70%. This meant that a 913 MW plant was required to generate 5.55 TWh/y. They employed the EIO-LCA method to develop their estimates of life cycle GWP emissions. They used a decay function to estimate the amount of CO_2 that would remain in the atmosphere after 20 years' operation, and they reported their results for GWP on this basis, 20 years after plant construction.

The results of Pacca and Horvath *(2002)* for renewable technologies are used to compare with LCA analyses of fossil-fuel technologies developed in the present paper. Our approach differs from that of Pacca and Horvath *(2002)* in that we report Total GWP for plant construction and 20 years' operation without discounting early emissions via a decay function. We prefer reporting total emissions because it is simpler and because it is believed that to a good approximation, global warming due to anthropogenic GHG emissions will be determined by total emissions, irrespective of when they occur (*Wigley et al. 1996, Hoffert et al. 2002*).

Estimates of life cycle GWP emissions for IGCC systems with and without CO_2 collection and for a natural gas combined cycle plant are given in Table 6 as computed in this paper by use of the EIO-LCA method. The computed results are scaled to describe 913 MW plants. The estimate for emissions from a NGCC plant was computed using capital cost and efficiency data developed by EPRI (*2000*). The plant is state of art having 383 MW nameplate capacity. It operates at 53.5% net efficiency (HHV), which yields a specific carbon emission rate of 0.338 $kgCO_2/kWh$. Total plant cost is \$190 million (or \$496/kW). We used the GWP capital intensity factor developed for IGCC systems above, 0.41 $MtCO_2e/\$10^3$, to estimate the GWP for construction of the NGCC plant. We did not include a case for NGCC with CO_2 capture because analysis has shown this technology is not as cost effective as either NGCC without capture or IGCC with capture *(Ruether et al. 2002*).

Also included in Table 6 are GWP for three renewable technologies for power generation as reported by Pacca and Horvath (*2002).* It is noted that the entries in Table 6 for Solar PV and Wind farm do not include backup generators or storage needed to assure electricity on demand. Renewable technologies that depend on intermittent energy sources should be considered as part of a larger power system that provides for continuous electricity supply for a rigorous life cycle analysis. When computed in this way, life cycle emissions of GHGs will be increased over the values shown in Table 6.

Table 6 shows that provision of carbon capture reduces life cycle GWP emissions for IGCC systems by a factor of 7. It also shows that life cycle GWP emissions of IGCC with 90% carbon capture is about 3 times less than that of NGCC, a technology which in turn has less than half the emissions of IGCC without carbon capture. The Table also indicates that GWP emissions for IGCC with 90% carbon capture are less than those of Solar PV. Wind generation and dammed hydro have the lowest GWPs.

The present study as well as that of Pacca and Horvath (*2002)* has shown that for fossil fuel-based generators without carbon capture, GWP emissions during construction are negligible compared to emissions during a normal service life. It also shows that emissions due to mining become of greater relative importance when carbon capture is employed. In the absence of carbon capture, mining emissions contribute about 3% of lifetime GWP for the example in Table 6. With 90% carbon capture, however, mining emissions are responsible for over 20% of lifetime GWP.

More advanced designs for coal-based generation plants with CO_2 capture will be able to capture substantially more than 90% of carbon emissions. Designs being developed by Anderson et al. *(2000)* and by Mathieu and Iantovski (*1998*), for instance, both employ oxygen rather than air for combustion, which eliminates the need for solvent-based CO_2 separation as is employed in the design analyzed in this work. It has been estimated that 99.5% of CO_2 emissions would be captured in power cycles that employ oxygen for combustion (*Ruether et al. 2000*). Table 5 indicates that at this level of CO_2 capture, plant construction, stack emissions, and coal mining would all affect total system emissions of GHGs. In this case accurate estimation of GWP for construction and mining as well for stack emissions would be important to estimate life cycle GHG emissions.

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Table 1

Process-based Estimate of GHG Emissions for 381 MW IGCC Plant (w/o CO_2 capture)

(*Gorokhov et al. 2002*)

	CO_2, Mt	Methane, $MtCO_2e$	Nitrous oxide, $MtCO_2e$	Total GWP, $MtCO_2e$	Total GWP/MW, $MtCO_2e/MW$
Construction	4.1E+04	0.33E+04	53	4.4E+04	115
Demolition	0.55E+04	180	3	0.56E+04	14.7
Annual operation at 70% capacity factor	1.78 E+06	0.07E+06	n.a.	1.85 E+06	4860

Table 2

Economic Sector Classification and Cost by Plant Section (1998 dollars)

Plant Section	I-O Category	DOC Sector	Purchaser Price, $K	Adjustment factor	Producer Price, $K
Coal & Sorbent Handling	Machinery/Conveyors	460200	7603	1.37	5550
Coal & Sorbent Prep & Feed	Machinery/Gen.ind.	490700	11480	1.12	10300
Feedwater & Misc. Balance of Plant Systems	Other met. prod./Pipes, valves	420800	8097	1.19	6800
Gasifier & Accessories	Other met. prod./Pipes, valves	420800	122191	1.19	103000
Hot Gas Cleanup & Piping	Other met. prod./Fab. met. prod.	421100	37832	1.19	31800
Combustion Turbine /Accessories	Turbines/Generators	430100	61888	1.08	57300
HRSG, Ducting & Stack	Other met.prod./Fab. met. prod.	421100	24983	1.19	21000
Steam Turbine Generator	Turbines/Generators	430100	27467	1.08	25400
Cooling Water System	Utilities/Water supply	680301	5766	1.00	5766
Ash/Spent Sorbent Handling Sys	Machinery/Conveyors	460200	5750	1.37	4200
Accessory Electric Plant	Elec. equip./Power transformers	530200	18990	1.28	14800
Instrumentation & Control	Instruments/Instr. meas. elec.	621100	5902	1.13	5220
Improvements to Site	Construction/Other repair & maint.	120300	2294	1.00	2294
Buildings & Structures					
Equipment Installation	Construction/Other repair & maint.	120300	194424	1.00	194424
Eng'g CM H.O. & Fee	Services/Eng'g, architect.	730302	42773	1.00	42773
Contingencies	Construction/Other repair & maint.	120300	96835	1.00	96835
TOTAL			**674275**		**627000**

Table 3

GHG Emissions for IGCC Plant Construction Computed by EIO-LCA[1]

(543 MW plant w/o CO_2 capture)

CO_2, Mt	Methane, $MtCO_2e$	Nitrous oxide, $MtCO_2e$	CFC, $MtCO_2e$	Direct GWP, $MtCO_2e$	Total GWP, $MtCO_2e$	Direct GWP/MW, $MtCO_2e/MW$	Total GWP/MW, $MtCO_2e/MW$
25 E+04	2.5 E+04	230	560	2.5 E+04	28 E+04	46	520

1. CMU *(2002)*

Table 4

Annual GHG Production for 543 MW IGCC Plant at 85% Capacity Factor[1]

Activity	Cost,[2] $ million	CO_2, Mt	CH_4, $MtCO_2e$	N_2O, $MtCO_2e$	GWP, $MtCO_2e$	GWP, $kgCO_2e/kWh$
Plant O&M	23.4	21500	1440	4830	28000	0.006
Coal Mining	21.0	16450	69400	1490	87400	0.022
Coal Transportation	9.20	8250	31	673	8960	0.002
Coal Consumption	---	3.25E+06	---	---	3.25E+06	0.804
Totals	53.6	3.30E+06	70900	6990	3.37E+06	0.834

1. CMU (2002)
2. 1997 dollars, producer cost

Table 5

Atmospheric GHG Emissions for Construction and Annual Operation of a

387 MW IGCC Plant with 90% CO_2 Capture at 80% Capacity Factor[1]

	GWP, $MtCO_2e$	GWP, $kgCO_2e/kWh$
I. Construction	26E+04	Not applicable
II. Operation		
Coal mining	6.6E+04	0.024
Coal consumption (net of CO_2 capture)	20.9E+04	0.091
Total annual operation	28E+04	0.115

1. CMU (2002)

Table 6

GWP for Construction and Operation of Electricity Generators for 20 y

at 5.55 TWh/y (111 TWh total), in Millions of $MtCO_2$ e

Technology	**Construction (% total)**	**Operations (% total)**	**Mining (% total)**	**Total**
IGCC w/o CO_2 capture[1]	0.47 (0.5%)	92 (96.9%)	2.5 (2.6%)	95
IGCC with 90% CO_2 capture[1]	0.57 (4.2%)	10.1 (74.9%)	2.8 (20.9%)	13
NGCC[1]	0.18 (0.5%)	38 (99.5%)	not computed	38
Hydro with dam[2]	0.8 (8-17%)	~6 (83-92%)	n/a	7
Solar PV[2]	20 (~100%)	0.07 (<1%)	n/a	20[3]
Wind farm[2]	1.3 (100%)	Negl.	n/a	1.3[3]

1. CMU (2002)
2. Pacca and Horvath (*2002).* Emissions due to biological processes vary over the project life. An exponential decay function is used in estimation of emissions due to operations.
3. Does not include backup generation or energy storage systems.