A Life Cycle Analysis of Electricity Generation Technologies:
Health and Environmental Implications of Alternative Fuels and Technologies

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GLOSSARY

Acid Mine Drainage - Drainage of water from areas that have been mined for coal or other mineral ores. The water has a low pH because of its contact with sulfur-bearing material and is harmful to aquatic organisms.

Discharges - Discharge of liquid effluent from a facility or to chemical emissions into the air through designated venting mechanisms.

EIOLCA – Economic Input-Output Life Cycle Analysis – A tool used to assess the environmental impact of a particular product or service by linking all the various economic transactions, resource requirements and environmental emissions required in its manufacture.

Greenhouse Gas - A gas, such as carbon dioxide or methane, which contributes to climate change.

SETAC/EPA Life Cycle Analysis - Holistically analyzing the cradle-to-grave environmental impact of products, packages, processes, and activities, from raw material acquisition to final disposition.

Particulate Matter - Fine liquid or solid particles such as dust, smoke, mist, fumes, or smog, found in air or emissions (PM2.5: smaller than 2.5 Micrometers in Diameter, PM10: nominally 10 Micrometers and less in Diameter).

I. INTRODUCTION

Increases in electricity demand and the retirement of old generating plants necessitate investment in new generation. Increasingly stringent environmental regulations, together with other regulatory requirements and uncertainty over future fuel prices, complicate the choice of appropriate fuels and technologies.

Electricity generation, a major source of CO_2, SOx, NOx, and suspended particles, also produces large quantities of solid waste, and contributes to water pollution. To make informed decisions about refurbishing old plants or investing in new ones, companies, concerned citizens, and government officials need good information about the environmental implications of each fuel and generation technology. New issues have surfaced recently, such as discharges of mercury and total greenhouse gas emissions. Since other potential issues loom, (e.g. other heavy metals), an environmental analysis must examine the life cycle of each fuel/technology, from extraction of the materials to disposal of residuals.

We review studies examining the life cycle environmental implications of each fuel and technology. We focus on the coal fuel cycle since: (1) it accounts for more than half of the electricity generated in the USA, (2) historically, the coal fuel cycle has been highly damaging to the environment and to health, (3) there are huge coal reserves in the USA, China, and Russia, and (4) the fuel is inexpensive to mine and likely to be used in large quantities in the future. We begin with an examination of the methods of life cycle analysis. We then present a brief historical overview of the research studies. Finally, we review and critique the alternative methods used for life cycle analysis. Our focus is the recent studies of the health and environmental implications of each technology. The studies agree that coal mining, transport, and combustion pose the greatest health and environmental costs. Among fossil fuel fired generators, natural gas power turbines are the most benign technology. Light water nuclear reactors received a great deal of attention in the early literature, but are neglected in recent U.S. studies. The earlier studies found that the health and environmental costs of light water reactors were low, at least for the portions of the fuel cycle that were evaluated. The studies did not evaluate the disposal of spent fuel and so are incomplete. Recent advances in life cycle analysis offer a large improvement over the methods of three decades ago and should help in choosing among fuels and technologies as well as modifying designs and practices to lower the health and environmental costs.

II. METHODS FOR LIFE CYCLE ANALYSIS

LCA is needed for informed decisions about alternative fuels and technologies. Modern LCA is divided into: (1) scoping, (2) discharge inventory, (3) impacts, and (4) improvement. Since a comprehensive analysis is impossible, each analyst must decide, explicitly or implicitly what will be considered in the analysis.

EPA and the Society of Environmental Toxicologists and Chemists (SETAC) developed and formalized methods for conducting LCAs in the 1990s. The basic step is conducting mass and energy balances of each relevant process. Thus, the analyses tend to be time consuming and expensive. Unfortunately, the quantitative estimates have been uncertain and controversial. The results can change as designs change or as the scope of the analysis is changed. Holdren (1978) criticized electricity life cycle analyses for excluding important aspects and for taking insufficient care. An LCA can be quicker if the results from previous analyses are used for each process. Unfortunately, using old data lowers accuracy.

A new approach to LCA was developed using the national Input-Output table and publicly available environmental data by Lave and Hendrickson. This approach is quick and inexpensive.

The disadvantage is that it is at an aggregate level. In particular, the U.S. analysis is done for the 500 sector U.S. input-output matrix.

III. BRIEF HISTORICAL REVIEW

Lave and Freeburg (1972, 1973), and Sagan (1973, 1974) performed the first comprehensive analyses on the effects of power plants. They both found that coal posed significant environmental risks, from mining, transport, and generation. Both found that oil and natural gas have much smaller environmental and health costs. Finally, both found that light water reactors have an even lower health burden, although neither could assess the environmental and health burdens of dealing with spent fuel, decommissioning old reactors, or of potentially catastrophic events.

Morgan, Barkovich and Meier (1973) focused on coal, again finding major problems. Other early studies were: Lave and Silverman (1976), Zebroski and Levenson (1976), Morse and Simmons (1976), Kruger (1976), Rattien and Eaton (1976), Post (1976), Golueke and McGauhey (1976), Gregory and Pangborn (1976), Kalhammer and Schneider (1976), Somers and Berg (1976), Budnitz and Holdren (1976), Comar and Sagan (1976), Morris (1976), Weills (1976), Holdren (1978), Holdren, Morris and Mintzer (1980), Inhaber (1980), Bolin (1977, 1980), and Tsoulfanidis (1981). More recent papers have examined new technologies and newer data ORNL-RFF etc. Studies have performed LCAs for other nations (e.g. Bates, (1995) Kivisto (1995) and Uchiyama (1996)). Two recent studies used a new life cycle analysis tool (Pacca (2002) and Meier (2002)).

Peters (1994) examined environmental burdens and impacts. Tahara (1997) compared several fuel cycles using CO_2 payback times (the time required to "payback" the CO_2 emitted from constructing the power plant). Norton (1999) found that renewable technologies, such as wind, hydro, solar-thermal and photovoltaic, are less attractive environmentally when evaluated using an LCA. Aumonier (1998) noted that LCA information is valuable in pointing out unattractive options. Karlsson (1998) describes an inventory analysis method specifically for environmental assessment of electricity in Sweden.

Many studies evaluate the global warming potential (GWP) of a fuel/technology. Table 1 shows Pacca's (2002) estimates of the cumulative GWP of power plants using different fuels (coal, hydro, PV, wind farm, and natural gas).

Gagnon et al (2002) reviewed previous LCAs. This study focused on hydropower (run-of-river and with reservoir), nuclear energy and windpower. They concluded that, although many studies have demonstrated technological innovation that promises to reduce emissions in one phase of the life cycle, it often increases it in others. They also suggest considering reliability in the life cycle analysis by including the backup power required to achieve the same level of reliability. The environmental issues associated with management and storage of spent nuclear fuel as well as the potential for catastrophic events is only mentioned briefly while a considerable portion of the paper discusses the excellent performance of nuclear energy. This paper also suggests that estimates of land use should include the land that is damaged due to climate change and acid rain.

IV. COAL

The fuel cycle of coal is shown in Figure 1. We focus on comprehensive studies conducted by research teams at The Oak Ridge National Laboratory-Resources for the Future (ORNL-RFF), Argonne, and National Renewable Energy Laboratory (NREL). The ORNL-RFF study focused on valuing the externalities of producing power, NREL focused on a complete inventory of discharges of the main processes involved in producing the power (including the construction and decommissioning of the plant), and Argonne focused on the design of the plant and the quantification of impact on the environment.

The 1994 ORNL-RFF study, the most detailed of the three, was part of a series that also looked at natural gas, hydro, biomass, oil, and nuclear. Each study examined one plant in the U.S. Southeast and one in the Southwest U.S. The plants were selected on the basis of easily available data, but are not representative of most plants in the USA. The 1999 NREL study assessed the environmental impacts of three pulverized coal boiler systems: a currently operating plant, a plant that meets the New Source Performance Standards (NSPS), and a Low Emission Boiler System (LEBS) based on the design of a potential future plant. The 2001 Argonne study focused on an advanced technology, an integrated gasification combined-cycle (IGCC) plant design based on the Shell entrained-flow gasifier. The IGCC was used either to produce electricity or to produce both electricity and hydrogen. The assumptions made for the three studies are summarized in Table II.

Environmental standards for coal combustion have tightened considerably over the past few decades. For example, the current New Source Performance Standards (NSPS) are 0.60, 0.60, and 0.03 pounds per million BTU of energy from coal for NOx, SOx, and suspended particles, respectively. A low emissions boiler has emissions standards 1/6 of the NSPS for NOx and SOx, and 1/3 of the NSPS for suspended particles. Similarly, standards for underground mine safety, acid mine drainage, and restoration of strip mined land have also gotten more stringent over time.

A. MINING

Problems from coal mining, include: injuries and chronic lung disease in miners, acid mine drainage, unrestored mining sites , dumping hill tops into neighboring valleys, air pollution, erosion, mining waste, subsidence, and disruption in underground water flows and storage. The environmental aspects of mining have received little analysis.

U.S. coals vary in moisture content (2-40%), sulfur content (0.2-8%) and ash content (5-40%). The energy content varies from lignite to sub bituminous to bituminous coal. The ORNL-RFF study looks at two sulfur contents (0.7% and 2.1%). The NREL and Argonne studies focused on high sulfur coal (Illinois #6), providing no information about the range of coals currently used in the USA.

The ORNL-RFF study assumed the coal came from surface mining. The NREL study examined the impacts of underground (longwall) and surface (strip) mining but concluded that the results were not significantly different. The Argonne study assumed underground mining, but did not conduct a full analysis of the impacts of mining.

B. TRANSPORTATION

Coal is transported by rail, barge and truck. The environmental impacts and injuries vary considerably across modes. The ORNL-RFF estimates for rail injuries and deaths are shown in Table III. Transporting coal causes nearly 400 deaths annually, where almost all deaths occur to members of the general public.

C. ELECTRICITY GENERATION

Resources required to build the power plant were considered, but some studies gave little detail. The ORNL-RFF study examined steel, concrete, land, and water. The coal feed requirements were taken into account in order to estimate the mining impacts (e.g. accidents), transportation impacts (e.g. road damage), and generation impacts (e.g. NOx emissions). The studies did not consider the resources or environmental issues associated with opening a new mine or constructing a new transport system, since they assumed that coal came from existing mines and transport systems. .

NREL evaluated concrete, steel, aluminum and iron, analyzing the resources used in the mining and transportation phases of the fuel cycle, including the transportation vehicles, land reclamation activities and mining equipment.

D. TRANSMISSION OF ELECTRICITY

Transmission has been neglected in the three major studies and more generally. While transmission is needed for all electricity, fuels are located different distances from power plants and the plants are located different distances from consumers.

Other studies have attempted to evaluate the environmental impacts of transmitting electricity. Linke and Schuler (1988), DeCicco, J.M. Bernow, S.S. Beyea, J. (1992), Kalkani and Boussiakou (1996), and Knoepfel (1996) evaluate transmission. The impacts appear to be small, unless there are important health consequences from exposure to 60 hertz electromagnetic fields. Knoepful (1996) develops and tests a framework for comparing the environmental impacts associated with various methods of shipping energy in Europe. This study concluded that for coal, generating electricity early in the fuel cycle and shipping the energy through high-voltage transmission lines can lead to significant impact reductions when compared to coal transport by barge and train. The results for oil and gas were not as clearly beneficial but have potential for environmental improvements.

E. ENVIRONMENTAL DISCHARGES AND IMPACTS

The studies considered a wide range of discharges, from air pollution emissions to water pollution discharges to global warming gases.

The ORNL-RFF study, characterized rather than measured or calculated additional impacts. NREL distinguished between human health and ecological health when discussing the impacts associated with the production of electricity. There was no attempt to estimate the dollar loss or magnitude of these impacts. Argonne considered: (1)) The natural environment impacts considered were acidification, eutrophication, smog, global climate changes, and ecotoxicological impacts (aquatic and terrestrial toxicity), (2) the human health impacts included toxicological impacts, PM10 inhalation effects, and carcinogenic impacts, and (3) the natural resources impacts (the depletion of fuels and consumption of water). Argonne made an attempt to calculate the relative impact of the plant designs studied.

Table V shows that modern technology can lower the adverse discharges from a coal-fired generation plant, due both to greater efficiency and better processes. SOx and NOx emissions can be lowered by almost a factor of ten and suspended particle emissions by a factor of 100. Since little or no attention has been given to CO and HC, the new technologies have little effect.

F. OTHER CONSIDERATIONS

1. Abandoned Coal Mine Problems

Abandoned coal mines are ubiquitous, as shown in the Office of Surface Mining's (OSM) map (Fig. 2). Funding for site restoration is small. For example, Pennsylvania is estimated to need $15 billion worth of restoration work, while the tax collected from coal mining operations available to Pennsylvania is only about $21 million per year.

The "High Priority" Problems monitored by the OSM are listed in Table V.

2. Acid Mine Drainage

Acid Mine drainage is the main cause of polluted water in the U.S. with devastating effects on biological activity in many streams. In 1995, 2400 of 54000 miles of streams in Pennsylvania were polluted by acid mine drainage from old mining operations. The summary data from OSM shows that there are still a total of 4688 miles of waterways that are affected by acid mine drainage; the cost of reclaiming those waterways is approximately $ 3.8 billion. Other organizations estimate that the total costs to reclaim waterways from acid mine drainage are much higher ($5 billion in PA alone). While measures have been put in place to minimize the effects of acid mine drainage, it still occurs in abandoned mines as well a small percentage of new mines.

3. Coal Mine Fires

Coal mines contain hazardous or explosive gases and there is a potential for long lasting fires. The OSM estimates that there are currently 4163 acres burning, including 94 sites where hazardous or explosive gas is being emitted from underground mine fires which can have an effect on humans in the vicinity of the site. The estimated cost of extinguishing these fires is $860 million.

The most extreme case in the U.S. is in Centralia, PA where an underground fire has been burning for over 30 years. Attempts to extinguish it have failed, leading the government to buy all the property at a cost of $42 million as well as costs associated with the attempts to fight the fire.

V. NATURAL GAS

Nearly all of the new generation in the USA in the past five years has been fueled by natural gas. NREL estimates that 22% of energy consumed in the U.S. is natural gas; DOE predicts that by 2020 33% of the electricity will be generated from natural gas. The life cycle stages of natural gas are construction and decommissioning of the power plant, construction of the natural gas pipeline, natural gas production and distribution, ammonia production and distribution, NOx removal, and power plant operation.

The ORNL-RFF study concluded that the major sources of damage from the gas fuel cycle are emissions of suspended particles and ozone. Finally, the gas fuel cycle has lower net emissions of CO_2 than other fossil fuel cycles but still has greater discharges than renewable energy sources. Other important environmental consequences of this fuel cycle are the potential for pipeline fires and explosions as well as drilling mud.

A summary of the results obtained from LCA of natural gas can be seen in Table VI. There is good agreement between CO_2 emissions of the various studies reviewed. It can be seen, however, that the assumptions made about the plants considered are very different.

VI. HYDRO

Until recently, hydroelectric power was considered the most environmentally benign form of electricity. In recent years, however, many people have concluded that hydro may be one of the worst fuel cycles in terms of environmental damage. The ORNL-RFF study was based on 1990 Pace report, which has been widely criticized. It states that most major waterways that have the potential to be used as hydroelectric generators in the United States have already been developed. However, projects involving retrofitting current dams as well as smaller scale diversion structures are possible. This study states that there are more than 77,000 dams with the potential for hydroelectric power development.

The discharges from the hydroelectric fuel cycle are shown in table VII. These values represent the discharges experienced in producing the materials to construct the hydroelectric power plant.

VII. OIL

Since the mid 1970s, oil has generated less electricity. In 1999, 3.3% of the electricity generated in the U.S. was generated using petroleum. The ORNL-RFF study investigated a hypothetical plant to be built in 1990. It was assumed that effective pollution abatement technologies would be installed.

VIII. NUCLEAR

107 nuclear power plant facilities were operating in the U.S. in 1997. No new permits to construct nuclear power plants have been issued in three decades and there are no applications imminent in the U.S. A major advantage to nuclear power is that generation does not release the pollutants that are a problem with fossil fuels. However, there are major concerns about the treatment and risks associated with the generation and storage of radioactive wastes and the possibility of a catastrophic release of radioactive material, as occurred at Chernobyl. Since the 1970s little assessment has been done in the U.S., in contrast to studies in other nations (Beck, 1995). An ORNL-RFF study investigates two hypothetical plants using pressurized water reactors. This is not state of the art technology but reflects typical plants in the U.S. today. However, the study was conducted as if a new plant were being built with this technology.

IX. BIOMASS

Biomass is a renewable fuel that could substitute for much of the current coal being used. Rafaschiari (1999) compared an integrated gasification combined cycle plant fired by dedicated energy crops (poplar short rotation forestry) to a conventional power plant. They found that biomass had less environmental impact than coal in almost all of the eco-indicators and normalized effects considered in this study. The most significant environmental effects from this fuel cycle are caused by the use of chemicals and fertilizers.

Hanegraaf (1998) applied a method similar to life cycle analysis in order to assess the sustainability of ten potential energy crops in four European regions. They concluded that the use of crops to generate electricity is preferred to their use as transport fuels from both an ecological and socio-economical criteria. They recommended that annual crops for electricity, such as hemp, be considered for the Netherlands both for ecological and economic reasons. Finally, financial incentives are required to make these crops competitive fuels for electricity generation.

Faaij (1998) investigated the externalities of biomass based electricity production compared with power generation from coal in the Netherlands. This study looked at the affects on economic activity and employment through the use of input/output and multiplier tables. The average private costs of biomass were found to be almost double that of coal power generation.

Some studies focus on the greenhouse gas emissions of this fuel cycle while others insist that considering ecological and socio-economic sustainability of biomass crops is essential to gaining a clear perspective of this fuel cycle. A comparison of co-combustion between different biofuels and hard coal for electricity production from hard coal alone has also been conducted. Spath et. al. (2000) compared biomass to both coal and natural gas.

The ORNL-RFF study investigated two hypothetical plants. This study asserted that evaluating the costs and benefits of the externalities might change the perceived "potential" for this fuel. This study concluded that there are significant differences in damages and thus externalities, among different sites (for example, benefits from erosion reduction differ by a factor of three) and for different biomass technologies. The use of advanced biomass conversion technologies could reduce NOx emissions significantly compared to conventional wood burners. This biomass fuel cycle has near-zero emissions of CO_2. This study therefore concluded that, compared to fossil fuel cycles, biomass is a less environmentally harmful fuel cycle in terms of impacts on global climate change.

X. WIND

Wind power has been used by humans for thousands of years. It has been used to generate electricity (on a small scale) since the early to mid 1900s. By 1995, it was estimated that there were 17,000 commercial wind turbines in the United States. The main advantage of wind is that the generation phase does not emit environmentally harmful pollutants. However, there are several major issues to consider. First, the amount of energy that can be extracted from wind goes up with the cube of wind speed. Thus, wind is economically attractive only where the wind blows nearly all the time at speeds of about 25 miles per hour. In evaluating wind, it is important to account for the environmental impacts associated with the manufacture of the wind turbines as well as the land used for the wind turbine.

Lenzen (2002) recently reviewed studies concerning the environmental impact of wind turbines. They suggest using an input-output based hybrid technique in order to minimize the uncertainties as well as using a standardized method of assessment.

A general review of the technology, design, trends and their subsequent environmental impact have also been conducted by McGowan et al (2000).

XI. SOLAR

The sun is the earth's greatest source of energy and the source of all renewable energy. The sun radiates energy (approx. $2.1*10^{15}$ kWh per day on earth) in the form of electromagnetic radiation. Although biomass, hydro, and waves are indirect forms of solar energy, the direct use of solar energy to generate electricity is either solar thermal or photovoltaic. Solar thermal technology uses the radiation directly to heat water. Photovoltaic technology converts the sun's rays directly to electrical energy. One of the advantages of solar radiation is that the conversion of electromagnetic radiation to electricity occurs without environmentally harmful discharges. However, other stages of the fuel cycle do contribute to environmental damage. One of the major environmental issues with this fuel cycle is the manufacture and disposal of solar cells and other equipment required to capture the radiation before it is transformed into electricity.

The renewable technologies, except for wind, are not used widely anywhere in the world because of their cost. Since the technology will not be disseminated widely until its costs are comparable, we assess promising prototypes. Many studies evaluate the environmental implications of fuel cycles in terms of their contribution to global warming. This is only one aspect of the life cycle and may mislead readers.

Mirasgedis (1996) estimated the level of atmospheric pollutants emitted during the manufacturing process of solar water heating systems. The study found that the LCA gaseous pollutant emissions from the production of solar water heating systems are much less than generating electricity through conventional means in Greece.

Greijer (2001) evaluated the environmental life cycle implications of a nanocrystalline dye sensitized solar cell and compared this to a natural gas combined cycle power plant. This evaluation focused on CO_2 and SO_2 emissions per kWh. They found that the gas power plant emitted about 10 times the CO_2 emissions of the solar cell. The largest impact from the solar cell was the process energy for producing it.

Koner (2000) looked at a photovoltaic generator and used the life cycle energy cost analysis to compare it to fuel generators (kerosene and diesel). He found that, at current market prices, the photovoltaic generators were comparable or less expensive than the fuel generators.

The toxic and flammable/explosive gases of concern in photovoltaic power systems are silane, phosphine and germane as well as cadmium. Recycling the cell materials is possible but the environmental consequences must be considered. Depletion of rare materials is also a concern. Energy use in the manufacturing stage is the largest contributor to emissions. An LCA of solar systems should consider the system integration aspects such as energy storage and the treatment of imports and exports.

A new “solar chimney” is currently being planned in Australia which would have very different environmental implications than previous solar technologies investigated, especially if it became used on a large scale.

XII. CONCLUSIONS

A substantial amount of work has explored the life cycle implications of generating electricity using a range of fuels and technologies. This work has developed the framework and life cycle method as well as the implications of each fuel/technology. Most of the US research has focused on coal, since it is the fuel for more than half of the electricity that is generated. The early technologies for generating electricity from coal produced many deaths and injuries from mining and transport as well as highly polluted air and water due to acid mine drainage and burning the coal. Increasingly stringent regulatory pressure has lowered both the injuries and environmental pollution from the lifecycle of using coal to generate electricity. Large remaining problems are underground mining, transport of the coal, and CO_2 emissions from burning the coal. Although the technology exists to solve the remaining environmental problems, little of that technology has been implemented. Additional incentives will be needed to solve these problems.

Nuclear powered turbines are perhaps the most benign fuel/technology, with only relatively small amounts of injury and environmental discharges. Disposing of radioactive waste and protecting plants against mishaps or terrorists are not fully solved. The next most benign is likely to be natural gas. Biomass offers a solution to the CO_2 emissions problem, but this fuel is more expensive and may not be less polluting. Petroleum has been phased out of the US electricity fuel market over the last quarter century; it is no longer important. On a life cycle basis, the renewable fuels have much higher environmental costs than might be suspected from an examination of a single part of the fuel cycle.

We conclude that LCA has a major contribution to make in choosing among fuels and generating technologies, as well as in finding the parts of the fuel cycle of each that are most important to fix.

Tables

Total Lifetime GWP for Various Fuels/Technologies					
	Hydroelectric	Photovoltaic	Wind Farm	Coal	Natural Gas
Output (TWh)	5.55	5.55	5.55	5.55	5.55
Emissions (MT CO_2 equiv.)					
CO_2 (x 10^6)	0.51	1.1	0.82	86	51
CH_4 (x 10^4)	0.084	0.78	0.054	35	50
N_2O (x 10^4)	0.85	8.7	0.65	220	220
GWE (x 10^6)	0.51	1.1	0.83	86	54

Table I: Total Lifetime GWP for Various Fuels/Technologies (Source: Pacca)

Assumptions for 3 Coal Studies							
	ORNL-RFF	NREL			ANL		
	SE & SW Ref	Nat'l Avg	NSPS	LEBS	Base	Co-Product	IEA Case
Date of Study	1994	1999			2001		
Plant Size (Mwe)	500	360	425	404	413	76/423	646
Technology	PC	PC	PC	PC	IGCC	H2/CC	CC
Efficiency	35%	32%	35%	42%			
Capacity	75%	60%	60%	60%			
Type of Plant	Based on Two Reference Sites	Nat'l Avg	Avg attaining NSPS	LEBS	Design Simulation	Design Simulation	Comparative Study
Other Plant Details	Wet lime/limestone scrubber (90% efficient), Electrostatic Precipitator (99.2% efficient), Low Nox burners, can meet NSPS	Baghouse filter, FGC system, heat recovery steam generator, steam turbine	Same as Nat'l Avg except higher FGC efficiencies	Low Nox system with advanced burners, air staging, wet ash slagging system, enhanced FGC (CuO)	Conventional IGCC plant releasing CO2 by combustion of the synthesis gas in a gas turbine	Production of electricity and H2 as energy carriers, 90% of CO2 is recovered for disposal in geological storage	
Coal Type	Kentucky no. 9 and Navajo	Illinois no. 6	Illinois no. 6	Illinois no. 6	Illinois no. 6	Illinois no. 6	Illinois no. 6
Extraction and Processing	Surface mining only (strip and contour)	Raw Material Extraction, Equipment Manufacture, Coal Mining (Surface-strip and Underground Mining-longwall), Surface Coal Mining Reclamation Requirements, Coal Preparation and Cleaning - Jig washing (electricity and water required, refuse landfilled)			Underground mining, coarse cleaning at mine mouth (assumed refuse returned to mine)		

Transportation	Rail and Truck	Transport of chemicals/materials to the mine site and power plant as well as the transport of coal - railcar, railcar and barge, mine mouth	By rail only - coal losses from train considered, diesel fuel use, open rail cars loaded with crushed coal - did not include manufacturing diesel fuel or manufacture and maintenance of rail cars
Generation	Operation only	Operation, construction and demolition, Ash treated and landfilled or alternate use	Operation of power plant as well as Construction and Demolition of power plant, CO2 and hydrogen pipelines
Transmission	Not Considered	Not Considered	Not Considered
Data Sources	Coal Technology - DOE 1988 Coal Technology, water and solid emissions - Meridian 1989, EPRI 1989, DOE 1989 Material Requirement emissions - Meridian 1989	Power Generation - TEAM database, FETC (Utility Data Institute, 1993, 1993, & 1996; Keeth et al, 1983; U.S. EPA., 1985; Schultx, and Kitto, 1992; Combustion Engineering, Inc., 1981; Ladino et al, 1982; Walas, 1988; Collins, 1994; Larinoff, 1994; and Darguzas et al, 1997) Plant details - Avg and NSPS Plant - (Utility Data Institute, 1996),TEAM LEBS Plant - Ruth, 1997 Surface and Underground Mining - Bureau of Mines - Sidney et al, 1976 (surface) and Duda and Hemingway, 1976 (underground)	LCA Analysis - LCAdvantage, Process Design - ASPEN simulation

Table II – Summary of Assumptions for 3 Coal Studies (Source: ORNL-RFF, NREL, Argonne)

NSPS – New Source Performance Standards
LEBS – Low Emission Boilers
PC – Pulverized Coal
IGCC- Integrated Coal Gasification Combined Cycle
H2/CC – electricity and hydrogen as energy carriers with Carbon Capture

Number of Deaths/Injuries From Southeast Reference Site/Year by Rail (for 500 MW plant)							
		Public	Occupational				Total
			Trans.	Maint.	Other	Total	
Injuries	Low	0.7	2.1	3.7	0.37	6.2	6.9
	Mid	0.83	2.5	4.2	0.37	7	7.8
	High	0.97	2.8	4.6	0.43	7.8	8.7
Fatalities	Low	0.28	0.0052	0.0047	0.0013	0.011	0.29
	Mid	0.34	0.0062	0.0053	0.00155	0.013	0.35
	High	0.39	0.0071	0.0058	0.0017	0.015	0.41

Table III - Number of Deaths/Injuries From Southeast Reference Site/Year by Rail (Source: ORNL-RFF)

COAL Comparison of Emissions (tons/GWh)										
	ORNL-RFF		**NREL**			**Argonne**			**Pacca**	**Proops**
Emissions	Southeast Ref Site	Southwest Ref Site	Average	NSPS	LEBS	Base Case	Co-Product Case	IEA Case		
CO_2	1100	1200	1100	1000	820	750	440	89	760	1100
SOx	1.8	0.87	7.4	2.8	0.79					
NOx	3.0	2.3	3.7	2.6	0.60				20	
Particulate Matter (PM)	1.6	1.6	10	11	0.12					
CO	0.27	0.27	0.23	0.28	0.21					
HC	0.099	0.13	0.23	0.22	0.21					
Trace Metals										
As ($\times 10^{-4}$)	2.0	2.0	0.54							
Cd ($\times 10^{-6}$)	3.0	3.0	4.5							
Mn ($\times 10^{-4}$)	1.3	1.3	0.47							
Pb ($\times 10^{-5}$)	9.0	9.0	3.3							
Se ($\times 10^{-4}$)	0.50	0.50	4.5							

Table IV – Comparison of Emissions from Coal Studies (Source: ORNL-RFF, NREL, Argonne, Pacca, Proops)

OSM - Unreclaimed Public Health and Safety Coal Related Problems - By Problem Type			
Problem Description	Measured As	Units Unreclaimed	Cost of Reclaiming Problems (000$)
Clogged Streams	Miles	1,700	48,000
Clogged Stream Lands	Acres	25,000	190,000
Dangerous Highwalls	Feet	4,200,000	600,000
Dangerous Impoundments	Count	760	14,000
Dangerous Piles & Embankments	Acres	8,800	250,000
Dangerous Slides	Acres	4,700	72,000
Gases: Hazardous/Explosive	Count	94	2,800
Hazardous Equipment & Facilities	Count	2,600	26,000
Hazardous Water Body	Count	970	54,000
Industrial/Residential Waste	Acres	400	10,000
Portals	Count	5,600	21,000
Polluted Water: Agri. & Indus.	Count	540	100,000
Polluted Water: Human Consumption	Count	4,200	3,70,000
Subsidence	Acres	8,500	480,000
Surface Burning	Acres	440	17,000
Underground Mine Fire	Acres	4,200	860,000
Vertical Opening	Count	2,400	37,000
Total			6,500,000

Table V

OSM - Unreclaimed Public Health and Safety Coal Related Problems - By Problem Type

Source: Abandoned Mine Land Inventory (Current Database), Programs: Acid Mine Drainage Plan, Coal Interim Site Funding, Coal Insolvent Surety Site Funding, FRP, State Emergency Program, Pre-SMCRA Coal State/Indian Tribe Grant Funding

Natural Gas				
	ORNL-RFF	Pacca	Proops	NREL
Technology	CCGT	CCGT	CCGT	NGCC
Capacity (MW)	500	1000	340	505
Efficiency	45-47%		53%	
Output	3.2 TWh	5.5 TWh	2.4 TWh	
CO_2	640	460	680	440
SOx	neg.			0.32
NOx	0.50	20		0.57
Particulate Matter (PM)	9.9			0.13

Table VI – Comparison of 4 Natural Gas Studies (Source: ORNL-RFF, Pacca, Proops, NREL)

Hydroelectric		
Emissions (tons/GWh)	ORNL-RFF	Pacca
	2^o Emissions from Manufacture	Upgrade of existing dam (5.5TWh/yr)
CO_2	8.7	4.6
SOx	0.027	
NOx	0.074	0.077
PM	0.0052	

Table VII – Comparison of Emission from 3 Hydro Studies (Source: ORNL-RFF, Pacca)

Figures

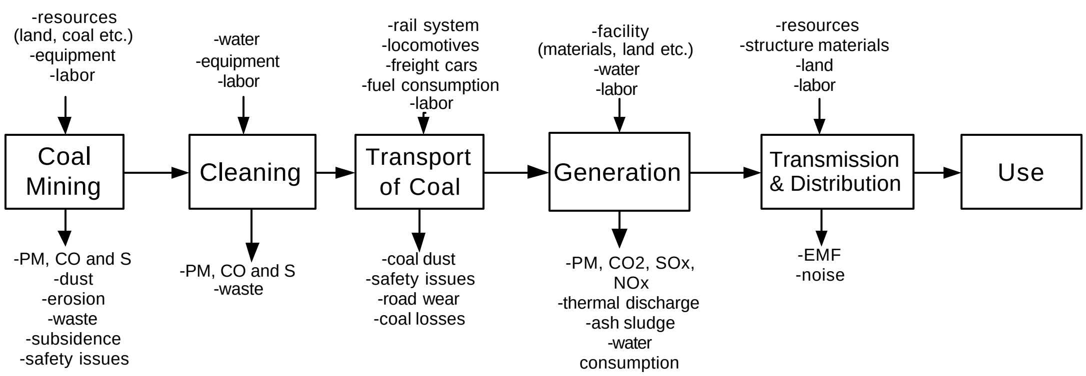
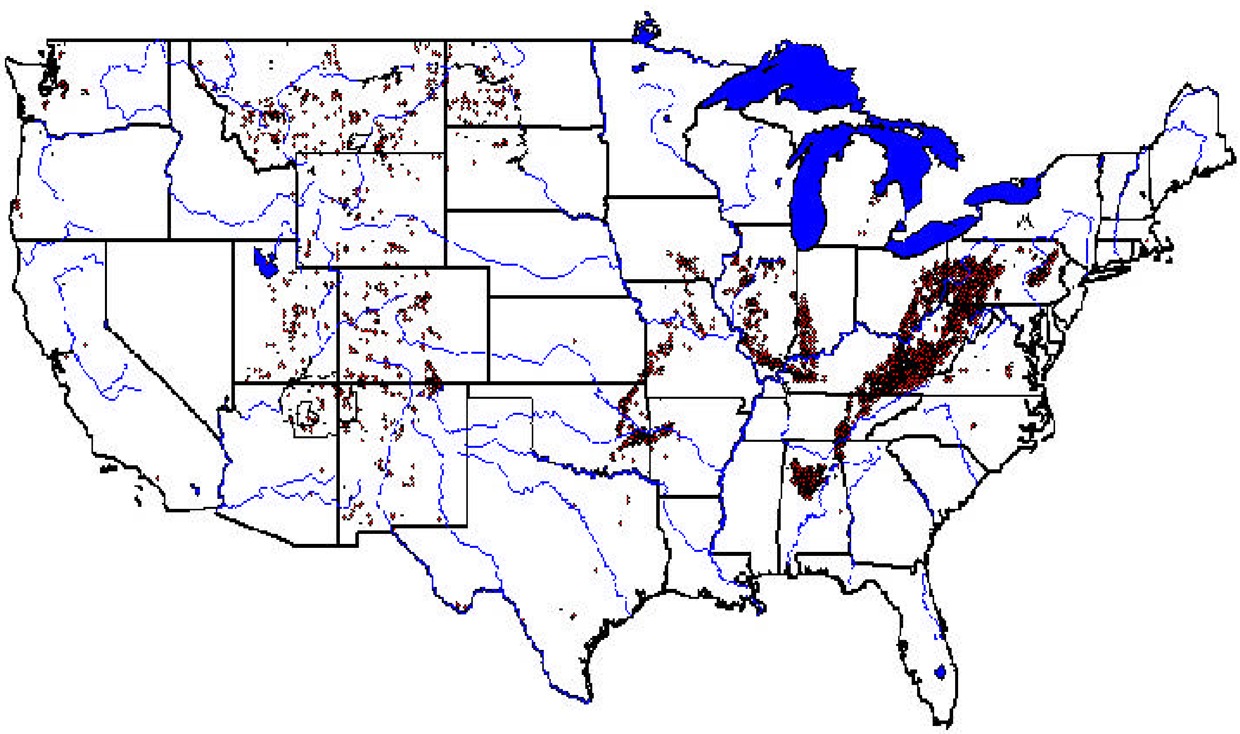


Figure 1



Locations of AML Problems Eligible for OSM Funding
http://www.osmre.gov/aml/intro/zintro2.htm
Figure 2

XIII. BIBLIOGRAPHY

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