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LIFE CYCLE ASSESSMENT OF GASIFICATION-BASED POWER CYCLES

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ABSTRACT

A suite of advanced, high-efficiency fossil-based power generation technologies, such as gasification-based technologies, is currently under development. Promulgation of stricter environmental regulations, as well as increasing fuel costs, mandates that these technologies not only be more efficient and economical, but also more environmentally friendly. Comprehensive quantification of the "full fuel cycle" environmental performance advantages of these new technologies is seen as critical to their future acceptance relative to conventional fossil-based technologies and non-fossil technologies. Life Cycle Assessment (LCA) is a well-accepted procedure for conducting such evaluations. LCA is a general analytical methodology used to quantify the environmental impacts of all manufacturing processes (including energy production) that convert raw materials (fuel) into final products (electricity). For the present study, a methodology was developed to conduct LCA for power generation systems. The methodology was subsequently applied to gasification-based power generation systems based on the results of ASPEN simulation modeling. A comparison of the environmental performance of the two power generation cycles is presented in this paper.

INTRODUCTION

Currently, nearly 75% of U.S. generated electricity is derived from fossil energy resources and recent projections indicate that fossil fuels will continue to be the primary source of electricity in the U.S. for the foreseeable future. In order to meet the future demand for fossil power production systems that can meet increasingly stringent environmental standards and improved operating efficiencies, a suite of advanced power generation technologies, including gasification-based energy conversion cycles, are being sponsored by the U.S. Department of Energy/National Energy Technology Laboratory (NETL). Gasification-based systems have the advantage of being able to co-generate electricity and fuel while meeting stringent environmental standards as required by changing regulatory requirements. Furthermore, these systems have the potential for near zero emissions of CO_2 by totally closing the carbon cycle through the use of renewables (such as biomass) as feedstock and by collecting a concentrated stream of CO_2 for sequestration.

Gasification-based technologies can be used to convert solid or liquid hydrocarbon resources into fuel gas or feedstock for synthesis gas conversion and/or combined-cycle power generation. These technologies, in various design configurations, are capable of co-producing a wide variety of commodity and premium products to meet future energy market requirements that demand clean and affordable energy. Compared with today's commercial power cycles, as well as other advanced power generation technologies, an integrated gasification combined cycle (IGCC), utilizing both steam and gas turbines, is among the most efficient and environmentally friendly technologies for the production of low-cost electricity and/or synthesis gas. Comprehensive quantification of the environmental performance advantages of these new technologies is seen as critical to their future acceptance relative to conventional fossil- and non-fossil-based technologies.

A project was recently performed at NETL to comprehensively evaluate two IGCC power systems based on a "full fuel cycle" (cradle-to-grave) analysis methodology. A well-defined life-cycle assessment (LCA) methodology was used to quantify the environmental impacts of all manufacturing processes (including energy production) that convert raw materials (i.e., coal) into final products (i.e., electricity). This paper describes both the analytical methodology and its results.

LIFE CYCLE ASSESSMENT METHODOLOGY

A well-accepted procedure for conducting a "full fuel cycle" evaluation is called Life Cycle Assessment (LCA). This is a general analytical methodology used to quantify the environmental impacts of all manufacturing processes (including energy production) that convert raw materials (e.g., coal) into final products (e.g., electricity). Although an intensive development of methods and techniques for conducting LCA has been going on during the last decade both in the U.S. and abroad, there are currently no approved standards or certification procedures for conducting product or process life cycle assessments. However, a generally accepted LCA framework has been defined by the Society of Environmental Toxicology and Chemistry[1] (SETAC), an organization that has emerged as the de facto authority on LCA. The International Organization for Standardization (ISO) is also developing a protocol for LCA as part of its development of the ISO 14000 environmental management standards. SETAC defines the inherent features of LCA as follows:

- A system-wide or "cradle-to-grave" perspective, implying coverage of the multiple operations and activities throughout a life cycle;
- A multi-media perspective, implying coverage of resource use and emissions to different environmental media, e.g., air, water, and soil; and
- A functional unit accounting system that normalizes energy carriers, material resources, emissions, and wastes across the system (e.g., full fuel cycle) and across media after unit process allocation procedures. Only those percentages of emissions or resource-use specific to the function are included in the balance sheet (LCA inventory table).

Figure 1 shows the methodological framework established by SETAC. SETAC currently recognizes four distinct components of a life cycle assessment. The first step is a ***goal definition and scoping*** activity that serves to define the specific objectives and the expected products of a given study, as well as to identify the intended audience for the results. Time and spatial boundaries are selected, boundary conditions and assumptions are defined, and impact and improvement objectives are established. The goal definition and scoping step applies to each of the subsequent three components of a life cycle assessment and can be revisited throughout the course of a study.

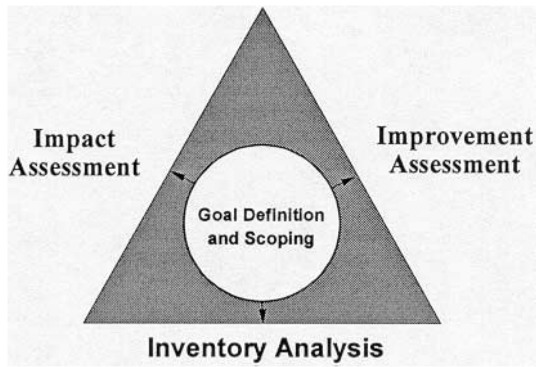


Figure 1. LCA Technical Framework

The second step, ***inventory analysis***, quantifies and catalogs the materials and energy used and the environmental releases arising from all stages of the life of a product or process, from raw material acquisition to ultimate disposal. The third step, ***impact assessment***, examines potential and actual environmental, human health, and resource depletion effects related to the use of resources (energy and materials) and environmental releases. The fourth step (optional) is an ***improvement assessment*** of the changes needed to bring about environmental, human health, and/or resource management improvements in the product or process. The project discussed in this paper covers the first three steps of the LCA methodology. The methods used to conduct both the inventory analysis and the impact assessment are described in greater detail below, along with their results.

LCA ANALYSIS OF TWO GASIFICATION-BASED POWER CYCLES

Goal Definition and Scoping

Two gasification-based power generation designs were selected for life-cycle analysis - - an oxygen-blown quench gasifier, and an oxygen-blown, entrained flow, slagging gasifier. To reflect the full life-cycle concept, both systems include three distinct activity areas:

- Gasification-based power plant island
- Auxilary operations and activities, including:
  - Extraction and processing of coal and other significant major natural resources

[1]SETAC is a worldwide professional society that was founded in 1979 to provide a forum for individuals and institutions engaged in the study of environmental problems, the management and regulation of natural resources, education, research, and development, and manufacturing and distribution. In 1990, SETAC conducted a workshop in an attempt to codify some of the techniques its members were using to conduct life cycle assessments. A basic methodology was agreed to at this meeting that the participants believed should guide life cycle assessments.

- Transportation of major consumables and construction materials to the power plant
- Byproducts and waste transportation/disposal/reuse
- Production of power plant consumables and construction materials

- Power plant construction and demolition

A brief technical description of the activities and equipment associated with each of these areas is presented below along with a listing of resource inputs and solid, liquid, and gaseous effluents. The quantities of materials, consumables, effluents and emissions associated with power plant island were obtained from ASPEN simulations.

A. Gasification-Based Power Island

The flow diagram for both cycles is shown in Figure 2. Both power plant islands include a gasification cycle, a fuel gas cleanup system, a steam cycle, a water treatment facility, and a cooling tower for steam cycle condenser cooling water treatment. The main differences between the two plants are the gasifier design, design of fuel preparation, solid waste (ash/slag) removal, and projected cycle efficicency. The gasification combined cycle, in both cases, includes:

- Coal Preparation module, based on Illinois #6 coal
- Gasifier
- Air Separation Unit (ASU) - high pressure process integrated with the gas turbine
- Gas turbine - W501 G modified for coal derived fuel gas
- Three pressure level subcritical reheat steam cycle
- High pressure water quench section for fast syngas cooling
- Cold gas cleanup (CGCU) for sulfur removal, based on Claus process

For the quench gasifier, Illinois #6 coal is crushed and mixed with water to produce a slurry that is 33.5% by weight water. This slurry is pumped into the gasifier along with oxygen. The gasifier is operated in a pressurized, downflow, entrained design and gasification takes place rapidly at temperatures in excess of 1260 °C (2300 °F). The raw fuel gas produced is mainly composed of H_2, CO, CO_2, and H_2O. The coal's sulfur is primarily converted to H_2S and a smaller quantity of COS. This raw fuel gas leaves the gasifier at 1260 to 1485 °C (2300 to 2700 °F) along with molten ash and a small quantity of unburned carbon. No hydrocarbon liquids are generated. The gas/molten solids stream enters a direct quench section, which consists of a large water pool, where gas is cooled and solidified ash particles are removed. The cooled raw fuel gas enters a gas scrubbing section to remove additional fine solids before exiting the gasification section to a gas cooling section.

The entrained-flow slagging gasifier is fueled with Illinois #6 coal that is pulverized and dried before being fed to the gasifier with a nitrogen transport gas. Coal, oxygen, and steam enter the gasifier through horizontally opposed burners. Raw fuel gas is produced from high temperature gasification reactions and flows upwardly with some entrained particulates composed of ash and a small quantity of unreacted carbon. The high reactor temperature converts the remaining ash into a molten slag, which flows down the walls of the gasifier and passes into a slag quench bath. The reactor temperature is controlled by using part of the heat of reaction to generate high pressure steam in the membrane walls of the gasifier. The raw fuel gas is quenched at the reactor exit with cooled recycled fuel gas to lower the temperature below the melting point of the ash. This avoids sticky solids entering the raw gas cooler. The raw gas cooler further cools the gas and generates high-pressure steam which is sent to the steam cycle. Solids are recovered in the following particulate filter and recycled back to the reactor. For both cycles oxygen (95% purity) is supplied by a high pressure cryogenic oxygen plant. A portion of the nitrogen (98.3% purity) is recycled to the gas turbine.

The raw fuel gas from the gas scrubber is cooled in a series of heat exchangers and sent to the cold gas cleanup unit (CGCU). Any hydrogen chloride and ammonia is assumed to be in the condensate from these heat exchangers, which is then sent to an ammonia strip unit for further treatment. This section also contains a catalytic hydrolyzer in which the carbonyl sulfide is converted to hydrogen sulfide. Heat recovered in the heat exchangers is used to generate low pressure steam from the HRSG and the ammonia strip unit. The clean fuel gas from CGCU is saturated with high pressure water condensate from the gas cooling unit before being sent to the gas turbine. This lowers the amount of nitrogen recycle from ASU needed to achieve the turbine power requirement to about 35%.

Cold gas cleanup and sulfur recovery are performed in the MDEA/Claus/SCOT process. In the MDEA step, the cooled gas from the low temperature heat recovery unit enters an absorber where it comes into contact with the MDEA solvent. As it moves through the absorber, almost all of H_2S and a portion of the CO_2 are removed. The solute-rich MDEA solvent exits the absorber and is heated by the solute-lean solvent from the stripper in a heat exchanger before entering the stripping unit. Acid gases from the top of the stripper are sent to the Claus/SCOT unit for sulfur recovery. The lean MDEA solvent exits the bottom of the stripper and is cooled through several heat exchangers. It is then cleaned in a filtering unit and sent to a storage tank before the next cycle begins.

Cleaned fuel gas is sent to a gas turbine. The exhaust gas stream of the gas turbine is further directed to a steam cycle. The steam cycle is a three-pressure level reheat process, which includes the following components: heat recovery steam generator (HRSG), steam turbines (high, intermediate, and low pressure), condenser, steam bleed for gas turbine cooling, recycle water heater, and deaerator.

The major resource inputs and solid, liquid, and gaseous effluents for the gasifier power island have been identified as:

- Major resource inputs: coal, water of different qualities, MDEA (used for removal of H_2S from the flue gas), catalyst for Claus process (used for promotion of a reaction between H_2S and SO_2 to form elemental sulfur), catalyst for SCOT process (used for conversion of unreacted SO_2 into H_2S), and auxiliary electricity
- Major products: electricity, and byproduct sulfur
- Solid waste: coal ash, spent Claus and SCOT catalyst, dewatered sludge from raw water coagulation process
- Liquid waste: gasifier blowdown, MDEA process blowdown, HRSG blowdown, cooling tower blowdown, water treatment unit blowdown
- Airborne residues: SO_2 from Claus plant, vent gas from SCOT plant, stack gas, deaerator vent, N_2 from the air separation unit, solid particulate drift from the cooling tower

B. Auxilary Operations and Activities

In addition to the main power generation module, several processes are located outside of the main module envelope as shown in Figure 2. Both cycles use these processes:

- Coal mining
- Coal cleaning
- Coal transportation to the power plant
- Solid waste collection
- Solid waste transportation
- Electricity transformation and distribution
- Waste water treatment

Run-of-mine (ROM) Illinois #6 coal was used in the ASPEN modeling to fuel both plants. It was assumed that this coal was mined underground, and either was not cleaned, or a very simple on-site cleaning at the mine mouth was performed. Emissions associated with coal transportation to the power plant mostly result from diesel fuel used by transportation vehicles and from particulate matter emissions from open rail cars loaded with crushed coal. Average emission data for all types of related transportation methods (e.g., rail, barge, and trucks) were used for delivery of bituminous coal in the U.S.

It was assumed that the power plant solid waste (ash and slag) was collected in a dewatering pond located on the power plant territory, and after dewatering it was transported to a landfill at a distance of 40 to 80 km from the power plant. It was also assumed that the landfill was designed to prevent leachate, and therefore emissions from solid waste collection and landfill are estimated as developed only from the fuel used for solid waste transportation by rail transport. Usually, sulfur developed in the Claus cycle is stored at the power plant and sold to clients. No emissions are expected from the sulfur storage process. Finally, according to selected water treatment process, most waste water does not require any treatment and can be discharged directly to the main water body.

C. Power Plant Construction and Demolition

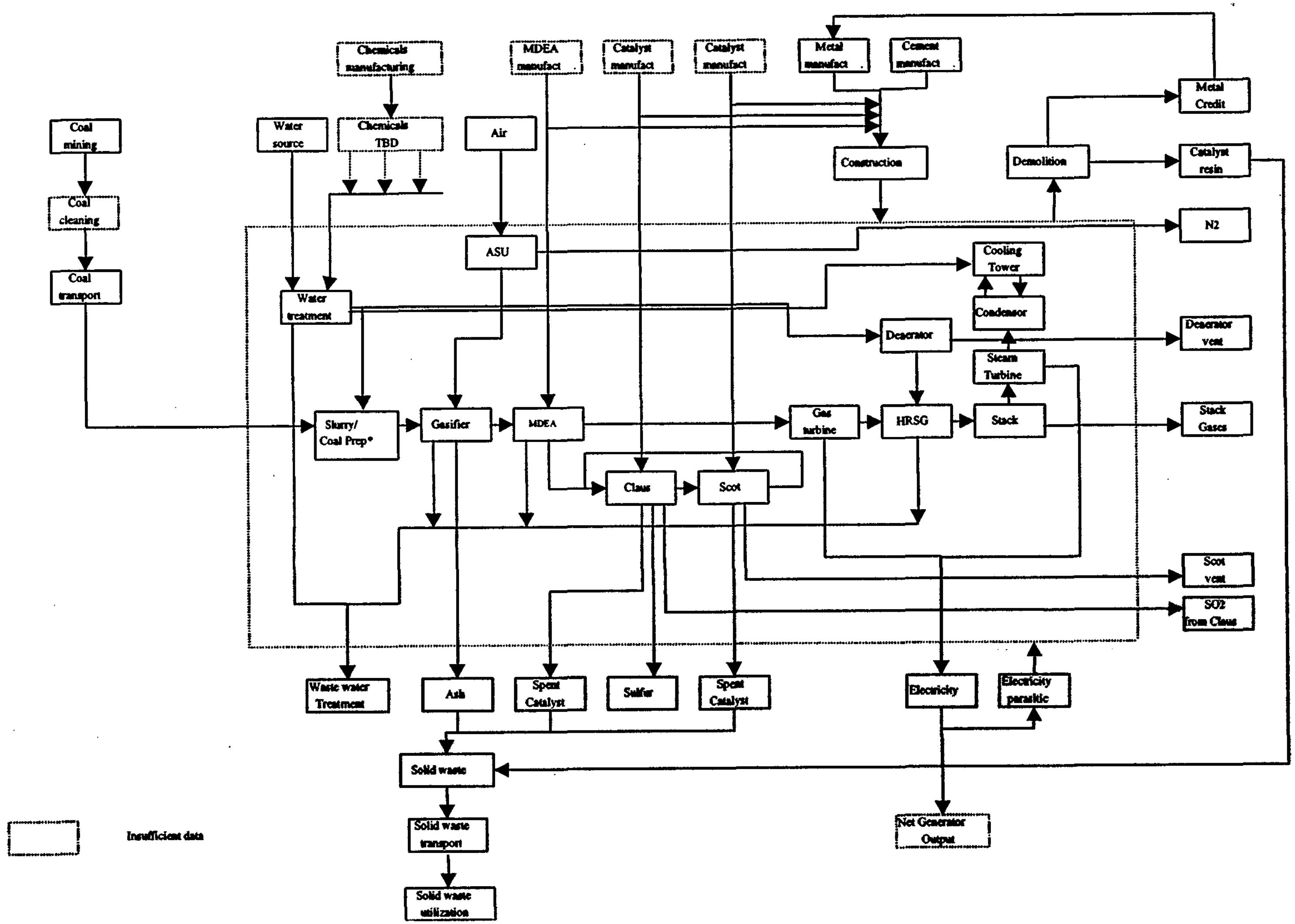
The power plant construction and demolition sections apply to both power plant cases. The amount of materials required for the construction of a power plant is broadly proportional to the size and complexity of the plant. The bulk construction materials required are essentially steel, cement, and aggregates in the ratio 1:1:6. This also includes aluminum, copper, glass and iron, but in insignificant amounts compared to the former three materials. Construction materials used for power plant construction, were estimated using data from [1,2,3] relative to their respective capacities of 381.6 MW and 407.1 MW: 18,182 tonnes of steel, 18,182 tonnes of cement, and 109,091 tonnes of aggregates for the power cycle with quech reactor, and 19,363 tonnes of steel, 19,363 tonnes of cement, and 116,381 tonnes of aggregates for the system with the slagging gasifier. Evaluation of emissions related to construction and the demolition aggregates emissions related to resource production and distributes them equally over the entire life of the power plant, (as recommended in reference [1]).

The energy requirement for manufacturing of steel, cement and aggregates was estimated to determine emissions associated with development and utilization of all kind of fuels and electric energy used directly in the steel, concrete, and aggregates manufacturing processes , as well as other emissions (particulate matter, organics, etc), emitted in the process of manufacturing. These requirements are estimated using data from [1,2,3,4,5,6], which appear to be very consistent. It is also necessary to take into account particulate matter (PM) emissions generated during the plant construction. As mentioned in [7], these emissions can be estimated as 1.1 tonnes/acre/month of activity. Land required for the construction is 200 acres and a construction period is 4 years. As such, PM emissions are estimated to be 1.1 * 200 * 48= 10,560 tonnes.

For both plant cases, the decommissioning of the power plant at the end of its useful life will involve some expenditure of energy depending on the future use of the site. It is advised in [1] that the net energy consumption for decommissioning can equal a nominal 10% of the energy consumed in the construction of the power plant. Emissions for decommissioning are therefore calculated on the basis of 10% of the emissions from the construction of the power plant.

There are two primary solid waste outputs of this activity area. One of them is the scrap metal that will be partially re-used for steel manufacturing. The second is spent Scot and Claus catalyst, and resins from the water treatment unit. This flow of material will be directed to the solid waste module and should be distributed over the assumed 30-year plant life (but alterna-

Figure 2. Flowchart for IGCC Power Plant LCA Analysis



tively could be assigned to the year after the power plant decommissioning).

Inventory Collection and Analysis Discussion and Results

Inventory collection and analysis were performed by using the LCAdvantage™ computer program developed by Battelle [8]. LCAdvantage™ combines life-cycle modeling features with a graphical user interface, database structure, and calculation engine. The database is comprised of U.S. basic commodities including power generation, fuels production and distribution, and cradle-to-gate operations for selected products such as metals, cement, and basic chemicals. The computer program and detailed IGCC operating data (from ASPEN simulations) were utilized to develop a customized inventory model of the primary IGCC process activities that result in a variety of pollutant emissions. This model aggregates emissions that occur throughout the entire energy cycle to develop a detailed inventory for the IGCC power system, including all materials and energy spent and products developed in the full fuel cycle. The quantities of materials, consumables, and effluents associated with IGCC process operations, as well as the pollutant emissions related to all relevant activities, were obtained from different sources, including the LCAdvantage database, other reports on LCA analyses, literature, EPA resources, and personal communications with individuals and experts in different industries. This data was vital for successfully conducting both the inventory and impact assessments.

In most cases, the difference in inputs and outputs (per kWh of produced electricity) for the two cycles is proportional to the difference in their cycle efficiencies. The main difference is in the cycles' net efficiency (HHV basis) is 39.6% for the cycle with the quench gasifier versus 45.4% for the cycle with slagging gasifier. This performance difference results in larger amounts of raw materials and fuel necessary for the first plant, as compared to the plant with slagging gasifier.

Materials used in largest quantities are bituminous coal and water. Other types of fuel and electricity are used mostly for coal extraction and transportation, and for solid waste transportation. Even though the amount of steel and concrete for construction of the power plant are significant, their amounts per kWh distributed over the 30 years of expected plant life are several orders of magnitude lower than the amounts of coal and water used for production of electricity.

CO_2 represents the largest component of the gaseous emissions, and most is produced in the power cycle. While the next largest amount is emitted in the coal extraction and transportation processes, it is two orders of magnitude lower than the emissions from the power cycle. CO_2 emissions are followed in magnitude by CO emissions, which are also released mainly in the power cycle. Methane released via coal mining represents the third largest emission. NOx emissions are of the same order of magnitude as SOx emissions. NOx emissions are associated mostly with coal extraction and transportation, while the SOx emissions are generated only from the power cycle operation. Almost all organic emissions identified in the inventory assessment are associated with use of fuel for extraction of coal and transportation of coal, waste, and construction materials.

As expected, significant particulate matter emissions are associated with coal extraction and transportation, and with the construction and demolition processes. It is interesting to note that when the construction and demolition particulate matter emission is levelized over the power plant life cycle, its amount (per kWh basis) is of the same order of magnitude as particulate emissions from extraction and transportation of coal. This is probably due to fact that the construction process includes all emissions associated with extraction of iron ore, development of cement and coke, transportation of these materials, and particulate emissions from the construction site itself. It is also very important to note that, in this analysis, these emissions are distributed over the 30-year period of the power plant life, while in reality all these emissions are released to the air shed in about a two year period during power plant construction. Thus, the local impact of these emissions can be very significant.

The largest quantities of solid emissions are represented by slag (for the slagging gasifier) and ash (for the quench gasifier).

Life Cycle Impact Assessment (LCIA)

LCIA is a technical, quantitative, and/or qualitative process of characterizing and assessing the environmental effects of the plant resource requirements and environmental loadings identified in the inventory collection step. Strictly speaking it should address all human health, ecological, and resource depletion impacts. This assessment approach reports the inventory results as a distillation of inventory loadings and resource use in the form of a category indicator with a numerical category indicator or index result. There is a category indicator for each environmental issue or category. These simplified category indicators are the basis used to make relative comparisons, considering improvement opportunities, or as potential problems for further investigation. The LCIA methodology includes the following steps [9,10,11]:

- Selection and definition of environmental impact categories and indicators (indexes) for each category;
- Classification of power system inventory results into the impact categories;
- Conversion of the inventory data within each category into the designated category indicator;
- Rating, weighting, or aggregating indicator results across impact categories to permit comparative

assessment between the two power systems and other technologies.

A broad spectrum of impact categories has been developed in the practice of LCIA. The number of selected categories and their nature generally influences the amount of work required to perform the LCIA. To streamline the LCIA, a minimum number of categories should be selected that can at least be expected to identify the relative differences between processes that are being compared – this is the approach taken in the IGCC evaluation project. Also, not all categories are equal in their analytical feasibility and prediction accuracy. This means that in some cases, even though the impact of a specific material or residue is real, there is not enough information, or a mechanism of the impact is not fully understood, to quantify potential hazard of this impact. The following criteria were used to select impact categories of interest to the IGCC evaluation project:

- The impact category should reflect concerns, which are specific for the process(es) under evaluation;
- The impact category should focus on areas where a difference in compared cycles is expected. If possible, categories dealing with the process or part of the process, which is similar for different comparing cycles, should be avoided; and
- The impact category should have at least a fair analytical feasibility, i.e. method(s) and supporting information for impact quantification should be well documented in validated sources.

Based on these criteria, 15 categories were selected as the most important for the evaluation of power cycles. These are identified below as aggregated into three broad impact groups:

Natural Environment - *acidification, eutrophication, smog, depletion of stratospheric ozone, global climate changes, and ecotoxicological impacts (aquatic and terrestrial toxicity);*
Human Health - *toxicological impacts, PM_{10} inhalation effects, and carcinogenic impacts*;
Natural Resources- *depletion of fuels, raw materials, water, and impacts on biological diversity*

After evaluation of the inventory data, some categories were eliminated because: 1) inventory results were very similar for both cycles (i.e., raw materials depletion), 2) no emissions were produced such that they would impact a particular category (i.e., stratosferic ozone depletion), and 3) not enough data were obtained to evaluate a particular impact category (i.e., biological diversity). This screening approach left 12 categories for the further analysis.

In general, some products, resources, and emissions can be involved in more than one impact category. Basically, four options are possible:

- Parallel mechanism -- the same emission/ product may contribute to 2 or more exclusive categories; and the emission should be divided or allocated to the relevant categories in order to avoid double counting;
- Serial mechanism -- an emission product may participate sequentially in 2 or more categories;
- Indirect mechanisms -- the product or result of one category, (e.g., original causing the release of another substance) may be the starting point for another category; and
- Combined mechanisms -- impacts caused by a combination of two or more types of emissions/products.

In order to deal with the complexities of the above-mentioned impact mechanisms, this initial LCIA procedure was simplified by: 1) accounting for primary emission impacts only, and 2) not distributing a particular product/emission among a number of different applicable impact categories, but rather assigning the full value of that product/emission to each applicable category. The latter assumption can be subject to criticism, because it is not physically correct. On the other hand, in order to apportion emissions among different categories, it would have been necessary to conduct a very complicated analysis/modeling, including the sequence and timing of events, potential chemical reactions, etc. Therefore, it was decided that, for the first attempt to compare power cycles via LCIA, the above assumptions were satisfactory.

The combined impact in each category is a result of aggregation of impacts of the independent emissions. Therefore, evaluation of relative overall emission loading or resource use requires some kind of a numerical index for each impact category. These indices are called category indicators, and usually incorporate a spectrum of results ranging from the technical values to subjective judgements. Since these indicators are the basis on which comparisons can be made, the value of a comparison is dependent upon the varying technical strength and relevance as well as the degree and type of subjective judgment used to derive a particular indicator. Some indicators can be estimated as just a total amount of a single material or emission such as water use, or PM_{10} emission. Other indicators can represent the total amount of different species. For example, land depletion resulting from landfill of waste can be represented by the total space occupied by all types of landfilled solid waste. In many cases data on individual chemicals or resources within an impact category need to be combined using so-called equivalency factors. These equivalency factors express the relative hazard potential of different chemicals within an impact category, but do not represent actual environmental impact. SETAC has developed numerous equivalency factors, and provides recommendations for development of new equivalency factors. A brief description is provided below for each category, together with the list of inventory items assigned to this category, as well as a basis for calculating category indicators with the relevant equivalency factors.

Acidification Acidifying substances cause a large diversity of impact on soil, ground water surface water organisms, ecosystems and materials (buildings). The most important acidifying compounds are SO_2 , NOx , and NH_3. Acidification potentials (AP) based on H^+ equivalents are used as equivalency factors to calculate the total indicator for acidification. The total indicator score is expressed in kg of SO_2 equivalents.

Eutrophication This category includes all impacts due to an excessively high level of macro-nutrients in the environment. Nitrogen (N) and phosphorus (P) are the most important eutrophicating elements. Eutrophication potentials (EPs) are used as equivalency factors to calculate the total indicator for eutrophication The total indicator score is expressed. The EPs reflect the potential contribution of a substance to biomass formation and is expressed in kg PO_4^{3-} equivalents. Major contributors to this impact for both power cycles are ammonia and NOx.

Smog or Photo-oxidant Formation Impact Photo-oxidants can be formed in the troposphere via photochemical oxidation of volatile organic compounds (VOC) or carbon monoxide (CO) in the presence of NOx and under the influence on UV light. Ozone is considered to be the most important oxidant. Photochemical ozone creation potentials (POCP) are used as characterization factors to calculate the total indicator for the formation of photo-oxidants, converted to kg of ethylene/kWh [12,13].

Global Climate Changes Global warming is the impact of fossil fuel emissions on the heat radiation absorption in the atmosphere. Major contributors are CO_2, methane, and N_2O. Global Warming Potentials (GWPs) are used as equivalency factors, to convert all amissions into kg of CO_2-equivalent/kWh.

Ecotoxicological Impacts These impacts are the effects of toxic substances on aquatic and terrestrial ecosystems. Only emissions to water and soil are taken into account in this impact category. Emissions to water are considered to be toxic only to aquatic ecosystems, and emissions to soil are considered to be toxic only for terrestrial ecosystems. Toxicity factors for these toxicity impact criteria were calculated using combination of the toxicity, persistence, and bioaccumulation properties of the inventoried chemicals to assess their potential fate and environmental effects. The toxicity data used for terrestrial toxicity, and aquatic toxicity were lowest rodent LD_{50} (mg/kg) and lowest fish LC_{50} (mg/l). A list of emissions, evaluated in this and in Human Toxicology categories includes more than thirty (30) (mostly organic) species.

Toxicological Impacts on Human Health This impact category contains the effects of toxic substances on humans. There are different ways for penetration of these substances into the human body (inhalation, water, food, and other), but only the inhalation effect is evaluated here. Factors for three toxicity impact criteria were calculated using combination of the toxicity, persistence, and bioaccumulation properties of the inventoried chemicals to assess their potential fate and environmental effects. The toxicity data used for human health is the lowest rodent LC_{50} (ppm).

PM_{10} Inhalation Impact PM_{10} inhalation impact on human health has an effect of chronic and non-chronic (short term) respiratory diseases, increasing both human mortality and morbidity rates in exposed areas. The equivalency factors were estimated as the total weight of solid particulate matter released to the atmosphere.

Carcinogenicity Impact That part of air toxins being exposed to the human body through oral or/and inhalation routes increase risk of cancer. The carcinogenicity equivalency factor is based on the weight-of-evidence (WOE) for carcinogenicity as described by either the International Agency for Research on Cancer (IARC) or the U.S.EPA [12,14].

Depletion of Fuel and Water These categories characterize depletion of so-called abiotic resources. The basis for resource depletion equivalency factors is the inverse of sustainability, which can be expressed as the world annual production of a mineral or a fossil fuel divided by the world reserve base [11, 12, 15]. For example, the fossil fuel data were based on global reserves and production, and were obtained from the Annual Energy Review for 1998 by the U.S. DOE Energy Information Administration [15]. The calculations include all types of fuel used in the power cycle, as well as in all other activities for manufacturing and transporation of all materials included in the inventory.

Depletion of Land This impact category focuses only on the loss of land as a result of coal mining or other fuel development operations, and use of land for waste landfill of waste. Because no specific place and type of coal mining were chosen, only use of land for landfill waste was evaluated in this project. The land-use equivalency factors for solid waste disposal are based on the estimated volume calculated using the specific gravity of each type of solid waste. Inventory data for solid waste is expressed in kg/kW; multiplication of the weight and the inverse of the specific gravity gives an indicator of the waste volume per kW, and thus, the landfill volume required per kW of developed energy.

A comparison of unweighted impact scores for all impact categories is presented in Table 1 for both power cycles. The last column in this table is a shorthand way of comparing the two processes from an environmental impact perspective. If values in this column are substantially larger than one, it indicates that the power cycle utilizing the quench gasifier has greater environmental impact than the cycle that utilizes the slagging gasifier, and vice versa. Values that within 20 percent of unity indicate that the impact potentials of the two cycles are not distinguishable [12]. The IGCC plant that utilizes the slagging gasifier shows a better performance in some of the categories such as acidification, eutrophication, and terrestrial, aquatic and human inhalation toxicity.

Table 1. Comparison of Unweighted Impact Scores for Two Power Cycles

Impact Category	Cycle with Quench Gasifier (Q)	Cycle with Slagging Gasifier (S)	Q / S
Acidification	3.83E-04	3.83E-04	1
Eutrophication	1.12E-04	3.16E-05	3.54
Particulate Matter (PM_{10})	4.03E-04	4.03E-04	1
Smog	2.84E-05	2.60E-05	1.09
Global Climate Change	1.74E+00	1.56+00	1.11
Terrestrial Toxicity	1.52E-04	8.34E-06	18.22
Aquatic Toxicity	5.16E-03	8.06E-06	640.20
Human Inhalation Toxicity	1.59E-01	7.38E-02	2.15
Carcinogenicity	2.89E-08	2.89E-08	1
Resource Depletion	3.21E-03	3.15E-03	1.02
Land Use	1.37E-04	6.47E-05	2.12
Water Use	1.26E+00	1.25E+00	1.008

SUMMARY

Comprehensive LCA inventory analysis and environmental impact assessment methodologies have been developed at NETL to investigate different types of power generation cycles. These methods, in conjunction with the results of ASPEN simulation modeling and information gathered from a variety of LCA sources, were used to evaluate the relative environmental performance of two different gasification combined cycles. The inventory assessment included models for fuel extraction, processing and transportation, power conversion systems, co-production, waste removal and landfilling, and plant construction/demolition. Detailed material and energy inventories were created for both cycles with the help of Battelle's LCAdvantage™ program. This inventory includes data on resources, products and emissions (gaseous, liquid and solid), either used or produced over the power plant lifetime. The full fuel cycle evaluation includes processes external to the power plant, such as resource extraction, processing and transportation of fuel, steel, concrete and other commodities and materials that are necessary for the power plant construction, operation, and demolition.

Natural resources utilized in the largest quantities are bituminous coal and water. Other resources utilized in significant quantities are steel and concrete for construction of the power plant. However, their normalized amounts per kWh, over the 30 years of the plant life, are several orders of magnitude lower than the cumulative amounts of coal and water used for production of electricity. CO_2 represents the largest component of the aggregate gaseous emissions. The primary quantity of CO_2 is produced via power production. The next largest amount of CO_2 is emitted from the coal extraction and transportation processes, but it is two orders of magnitude lower than the CO_2 emissions from power production. CO_2 emissions are followed by CO emissions, which are also released mainly in the power island. Methane emissions are associated with coal mining and represent the third largest emission. NOx emissions are of the same order of magnitude as SOx emissions. NOx emissions are associated mostly with coal extraction and transportation, while SOx emissions are emitted only from the power cycle. Particulate matter emissions are mostly associated with coal extraction and transportation, and with the plant construction and demolition processes. Almost all organic emissions are associated with use of fuel for extraction of coal and transportation of coal, waste and construction materials. Some organic emissions are also emitted during production of construction materials. Slag or ash represents the largest quantities of solid emissions.

Twelve impact categories were selected as most relevant to define the environmental impact of the fossil energy conversion systems. These categories were divided into three major groups by the geographic magnitude of an impact: global, regional and local. All inventory resources and emissions were assigned to their relevant impact categories, and the total score for environmental impact in each category was estimated on the basis of unique equivalency factors for each. Comparison of scores for each category indicates that, although both cycles have identical performance in most categories, the cycle with slagging gasifier exhibits a better overall environmental performance in some categories relative to the cycle with quench gasifier. Particular categories associated with better environmental performance for the slagging gasifier were: euthrophication, terrestrial toxicity, and aquatic toxicity.

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