A COMPARATIVE LIFE CYCLE ASSESSMENT REVIEW OF CONVENTIONAL PULVERIZED COAL – FIRED ELECTRICITY GENERATION AND UNDERGROUND COAL GASIFICATION (UCG) LINKED WITH AN INTEGRATED GASIFICATION COMBINED CYCLE (IGCC)

Curtis Enrico Meintjies

A research report submitted to the Faculty of Engineering and the Built Environment, of the University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

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CANDIDATES DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Curtis Enrico Meintjies

16th March 2011

ABSTRACT

In a global climate where sustainable development is being prioritized for the benefit of current and future generations, it is necessary to make informed decisions about the type of technologies being deployed. Because coal plays such a significant role in the generation of electricity, understanding the impact it has on the environment is an important part of understanding energy and environmental issues in general. To this end, a Life Cycle Assessment (LCA) was performed on two methods of electricity generation which employ coal as a primary source of energy. This assessment focused on the impacts from the power plants such as the emissions, resource consumption, and energy use of all processes required for the power plant to operate, including any necessary waste disposal and material recycling.

Two technologies were selected. A PCC plant which represents the average emissions and efficiencies of currently operating coal-fired power plants in the world, and an IGCC plant which uses combustible gas derived from an UCG plant, hence a UCG-IGCC plant. The results of the LCA suggest that UCG-IGCC technology is more sustainable than the conventional PCC technology. The results yielded significant reductions in environmental stressors related to air, water, resource consumption and waste used in the impact assessment.

Ultimately, LCA can be seen to be an ideal integrated environmental management tool to facilitate decision making on competing technologies to be deployed by assessing them throughout their entire life cycles.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

BFBC	Bubbling Fluidised Bed Combustion
°C	Degrees Celsius
CCT	Clean Coal Technologies
CCGT	Combined Cycle Gas Turbine
CBM	Coal Bed Methane
DEAT	Department of Environmental Affairs and Tourism
ESP	Electrostatic Precipitators
EMMA	Eco-model for Materials and Manufacturing Assessment
FBC	Fluidised Bed Combustion
FGD	Flue Gas Desulphurization
FEGT	Furnace Exit Gas Temperature
GTCC	Gas Turbine Combined Cycle
GGE	Greenhouse Gas Emissions
Gwh	Gigawatt Hour
GL	Giga Litres
HHV	Higher Heating Value
IEA	International Energy Agency
IEA CCC	International Energy Agency Clean Coal Centre
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel for Climate Change
ISO	International Standard Organization
kV	Kilovolt
Kg	Kilogram
Kg/s	Kilogram/second
kPa	Kilopascals
KW	Kilowatt
LHV	Lower Heating Value
LCA	Life Cycle Assessment
MW	Megawatt
MWh	Megawatt Hour
MPa	Mega Pascal
MVA	Megavolt Amperes
µm	Micro Meter
NMA	National Mining Association
NG	Natural Gas
NOx	Nitrogen Oxides
NGGIC	National Greenhouse Gas Inventory Committee
OECD	Organization for Economic Co-operation and Development
PM	Particulate Matter
PF	Pulverised Fuel
PPCC	Pressurized Pulverized Coal Combustion
PCFBC	Pressurised Circulating Fluidised Bed Combustion
PFBC	Pressurised Fluidized Bed Combustion
r/min	Revolution/minute
SABS	South African Bureau of Standards
SETAC	Society for Environmental Toxicology and Chemistry
SCR	Selective Catalytic Reduction
SNCR	Selective Non- Catalytic Reduction
SOx	Sulphur Oxides
SPM	Suspended Particulate Matter
UCG-IGCC	Underground Coal Gasification - Integrated Gasification Combined Cycle
UCG	Underground Coal Gasification
US EPA	United States Environmental Protection Agency
WCI	World Coal Institute

CHAPTER 1: INTRODUCTION

1.1 Background to Study

Energy is fundamental to almost every aspect of modern life and societies require increasing amounts of energy as they grow and develop. The demand for energy is growing worldwide. The International Energy Agency (IEA, 2009) projects that energy demand will grow at an annual rate of 2.5% to 2030. Over 80% of the growth takes place in non-OECD countries (IEA, 2009). Even then, 1.4 billion people could still lack access to electricity. To meet this need, the world will have to make the best possible use of the various energy sources available. This includes coal, the most abundant and affordable of the fossil fuels.

Coal plays a major part in the world's energy system and hence in global economic and social development. Coal currently supplies 40% of the world's electricity and 23% of global primary energy needs (WCI, 2003). Coal consumption is expected to grow by around 1.4% per year over the next thirty years (IEA, 2002). With its vast, low-cost resource base, there is no doubt that coal will continue to contribute to economic growth and social development. The abundance, affordability, geographical and political diversity of coal is important in a world ever more concerned with energy security. But industry recognises that it must also be able to meet the challenge of environmental sustainability. Coal combustion emits particulates, sulphur oxides, nitrogen oxides, mercury and other metals, including some radioactive materials, in a much higher proportion than oil or natural gas. Therefore, coal combustion causes local and regional pollution problems contributing to acid rain and increased ground-level ozone levels, and global climate change. Coal releases higher emissions of carbon dioxide than other fossil fuels, as coal's ratio of hydrogen atoms over carbon atoms and power generation efficiency are relatively low compared to other fossil fuels (WCI, 2006). Coal is also responsible for methane emissions, notably from mining (WCI, 2006). Hence, coal and other carbon intensive energy sources must significantly reduce their potential greenhouse gas emissions if they are to claim a continuing and sustainable role in the global energy mix. The technologies employed and being developed to meet coal's environmental challenges are collectively referred to as clean coal technology (CCT) (WCI, 2006).

In a global climate where sustainable development is being prioritized for the benefit of current and future generations, it is necessary to make informed decisions about the type of energy technology being deployed. Because coal plays such a significant role in the generation of electricity, understanding the impact it has on the environment is an important part of understanding energy and environmental issues in general. Life Cycle Assessment (LCA) provides a suitable tool for ranking environmental performance of technologies being considered. In this study, a LCA was performed on two methods of electricity generation which employ coal as a primary source of energy. These methods are: 1.] a conventional Pulverised Coal Combustion (PCC) plant, and 2.] a Gasification Combined Cycle Plant (IGCC) which uses combustible gas derived from an Underground Coal Gasification (UCG) plant. The emissions, resource consumption, and energy use of all processes required for these power plants to operate, including any necessary waste disposal and material recycling, will be assessed.

All resources, emissions, and energy flows for each system will be inventoried in a cradle-to-grave manner, including processes that are common between the two systems. These analyses can therefore be compared. The total environmental picture of each system can be discerned from this analysis. To quantify the total economic and environmental benefits and drawbacks of a process, a LCA can be performed in conjunction with a technical and economic analysis. The results of the LCA can be used to identify opportunities to reduce the environmental burden of the system through design improvements (Spath *et al*, 2009).

1.2 Problem Statement and Research Motivation

Society is demanding cleaner energy and less pollution. The coal industry is proactively responding to the call for improved environmental performance through the use and continued development of CCT's.

All forms of energy have positive and negative attributes. But given that energy demand is going to continue to rise and many challenges have to be met, it is necessary to review the energy options and balance these responsibly and reliably.

Environmental LCA is a good approach for ranking the 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. 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 emissions of a large number of individual compounds and classes of compounds discharged to the atmosphere, to waterways, and to the land.

The results on common aspects between the two technologies, namely, PCC and UCG-IGCC, will be subject to a comparative analysis. These results can then be used to identify opportunities to reduce the environmental burden of the systems through design improvements and as basis for comparison with other electricity generation technologies. The intended target audiences of the study include governments, energy agencies and utilities as the results may assist and aid in making technology selection decisions for new installations.

1.3 Aims and Objectives

The aim of the research is to evaluate the environmental sustainability of two coal based electricity generation technologies by using LCA as a means to assess the environmental aspects and potential impacts throughout their lifecycles (i.e. cradle-to gate) from raw material acquisition through production, use and disposal. The LCA will be conducted in accordance to the ISO 14040 Series on LCA which describes the procedures for conducting such an assessment. These include:

- ISO 14040 – Life Cycle Assessment – Principles and Framework (2006)
- ISO 14041 – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis (1998)
- ISO 14042 – Life Cycle Assessment – Life Cycle Impact Assessment (2000)
- ISO 14043 – Life Cycle Assessment – Life Cycle Interpretation (2000)

This aim of the research can be further expressed in four main objectives:

- Conduct LCA for PCC

- Conduct LCA for UCG linked with an IGCC

- Conduct a comparative analysis on common aspects between PCC and UCG-IGCC

- Conclude the study with discussion on the outcome of analytical results and provide recommendations

The Scope of the Study

All of the major processes necessary to produce electricity from coal such as coal mining, equipment manufacturing, transportation, and chemicals production for the mining and power plant operations have been included. The material and energy flows of processes involved in the extraction of raw materials and the production of intermediate as well as the disposal of wastes were also included.

The two coal based electricity generation technologies which were assessed include:

1. A PCC plant. This plant represents the average emissions and efficiency of currently operating coal-fired power plants in the world and;

2. An IGCC which uses combustible gas derived from an UCG plant. Hence a UCG-IGCC plant.

1.5 Structure of the Research Report

Chapter 1 of the research report presents an introduction to the research topic. It contains a brief background on the current and future global energy scenarios with particular reference to the dominance of coal. It also includes a problem statement and research motivation by the author as to why the research was carried out. This is followed by the aims, objectives and scope of the study.

Chapter 2 presents a critical literature review of the research topic, dealing specifically with: LCA and the nature, functioning and deployments of CCT's. These technologies include technologies deployed for preparation, efficient combustion and the reduction of emissions related to coal

Chapter 3 details the methodology used to conduct the study. It is primarily based on the four stage approach for conducting LCA recommended in the ISO 14040 guidelines. Furthermore, this section provides some insight and detail on the basis for comparison, system boundaries, assumptions on data accuracy and transparency as well as the basis for the impact assessment.

Chapter 4 deals with the actual LCA for the two coal based electricity generation technologies. Both the PCC and UCG-IGCC technologies are discussed with particular emphasis on their respective system characteristics and operational specifications, materials and energy flows, assumptions as well the result of the impact assessments. This is followed by a comparative analysis and discussion on findings.

Chapter 5 presents the conclusions and recommendations that the author derived from the research project in terms of the sustainability of two coal based electricity generation technologies.

Due to costs associated with LCA software, all the data collected and presented here is based on BHP Billton's LCA model called EMMA (Eco-model for Materials and Manufacturing Assessment). The use of software such as Sima Pro would enhance any LCA investigation, as long as the required inputs and outputs are included in the software to match the LCA project requirements.

CHAPTER 2: LITERATURE REVIEW

Having presented a succinct introduction to the research report topic in Chapter 1, a critical literature review of the research topic, specifically with regard to LCA and the nature, functioning and deployments of CCT's is presented in this Chapter.

2.1 Life Cycle Assessment

LCA is the calculation and evaluation of the environmentally relevant inputs and outputs and the potential impacts of the life cycle of a product, material or service (SABS ISO, 1998). Environmental inputs and outputs refer to the demand for natural resources and to emissions and solid waste. The life cycle consists of the technical system of processes and transport routes used at, or needed for, raw materials, extraction, production, use and after use (waste management or recycling). Both Benetto *et al* (2004) and Meier *et al* (2005) describe the concept as such. LCA is sometimes called a "cradle to gate" assessment.

LCA approaches are generally guided by standards but a professional code of practice has also been developed (Consoli *et al*, 1993).

LCA has generally four components. These include:

I. Goal and scope;
II. Inventory;
III. Impact assessment; and,
IV. Improvement assessment

From a standards perspective, LCA is dealt with under the umbrella of the ISO 14040 series. The documents are as follows:

- ISO 14040 – Life Cycle Assessment – Principles and Framework (2006)
- ISO 14041 – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis (1998)
- ISO 14042 – Life Cycle Assessment – Life Cycle Impact Assessment (2000)
- ISO 14043 – Life Cycle Assessment – Life Cycle Interpretation (2000)

ISO 14040 provides a model for the approach to undertake a LCA. The procedure for LCA, which is described below is illustrated in Figure 1.

I. Goal and Scope Definition

The product or service to be assessed is defined. A functional basis for comparison is chosen and the required level of detail is defined.

II. Inventory Analysis

The energy carriers, raw materials, emissions to atmosphere, water and soil and different types of land use are quantified for each process. These are all combined in the process flow chart and related to the functional basis.

III. Impact Assessment

The effects of the resource use and emissions generated are grouped and quantified into a limited number of impact categories which may then be weighted for comparison (DEAT, 2004).

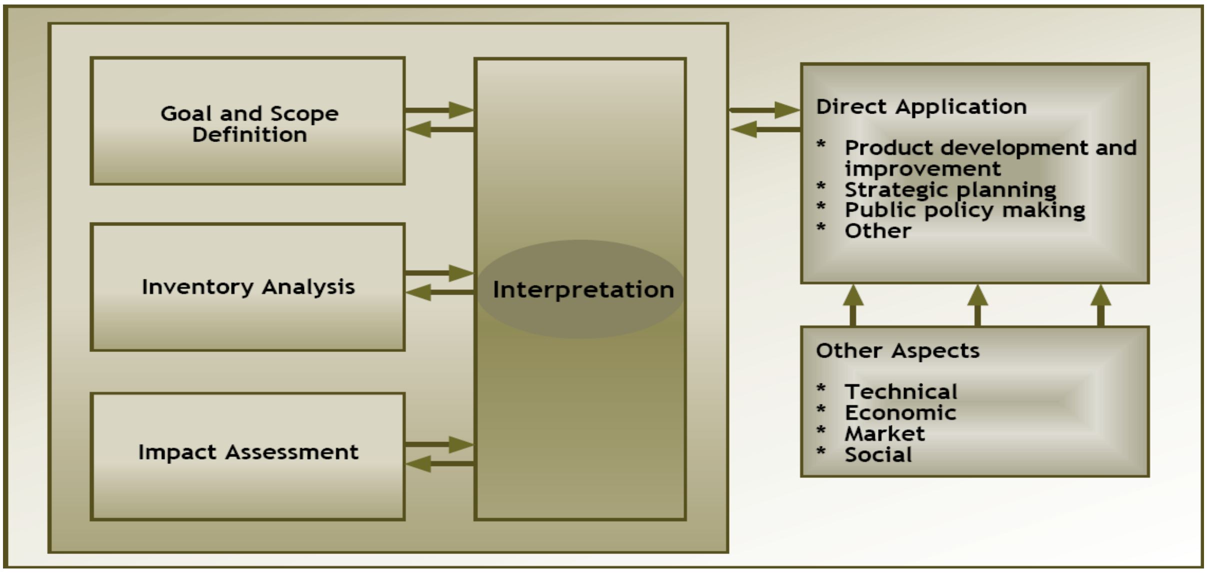


Figure 1: Illustration of Life Cycle Assessment Procedure (DEAT, 2004).

The various groupings of activities associated with a process, service, product or plant provide the basis for undertaking a LCA. The conceptual LCA will map the processes into a flow chart which broadly migrates from inputs (raw materials) through processing (product or production system) through to outputs (finished goods, by-products and wastes) which is illustrated in Figure 2. Simplified and detailed LCAs will, in various levels of detail and complexity, quantify, classify and categorise the impacts at different stages (DEAT, 2004).

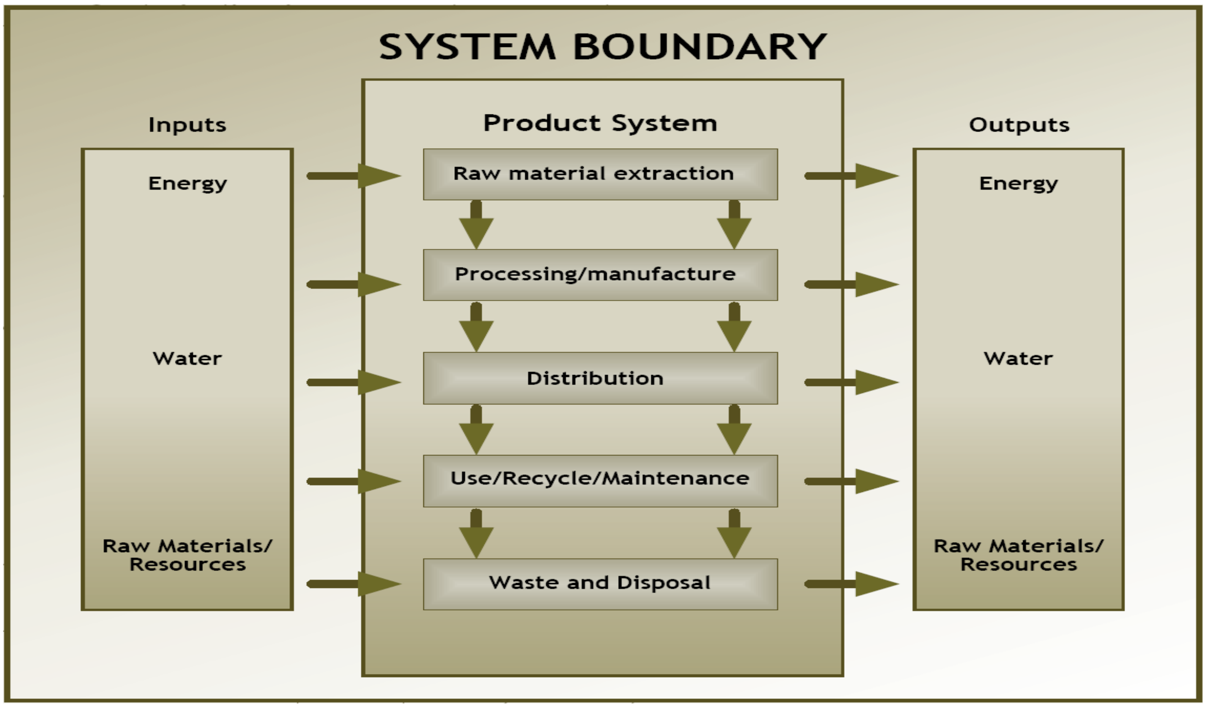


Figure 2: Life Cycle Assessment framework based on the ISO 14040 model (DEAT, 2004).

IV. Improvement Assessment

The Improvement Assessment is the phase where the results are analysed in relation to the goal and scope definition, where conclusions are reached, the limitations of the results are presented and where recommendations are provided based on the findings of the preceding phases of the LCA.

2.2 Clean Coal Technologies

The technologies employed and being developed to meet coal's environmental challenges are collectively referred to as CCT's. CCT's represent a continuously developing range of options to suit different coal types, different environmental problems, and different levels of economic development. In this section, all CCT's were discussed in general. Particular attention was then further given to PCC, IGCC and UCG as they formed the basis of the comparative study.

According to the World Coal Institute (WCI), (2003) and the National Mining Association (NMA), (2003), CCT's can be said to have three core elements:

1. Eliminating emissions of pollutants such as particulate matter and oxides of sulphur and nitrogen. This has largely been achieved and the issue now is the application of 'off-the-shelf' technology.

2. Increasing thermal efficiency to reduce carbon dioxide and other emissions per unit of electricity generated. Major gains have already been achieved and further potential can be realised.

3. Eliminating carbon dioxide emissions. The development of 'zero emissions technologies' has commenced and is accelerating rapidly.

CCT's can be implemented pre, during and post combustion to alleviate the typical environmental impacts related to coal based electricity generation. Aspects related to 1. coal preparation pre-combustion, 2. during combustion utilisation and 3. post combustion control of emissions are discussed further with specific emphasis on PCC, IGCC and UCG.

2.2.1 Coal Preparation (Pre-Combustion)

As-mined coal is of variable quality and contains substances such as clay, sand and carbonates. Coal preparation – also known as coal beneficiation or coal washing/cleaning – is the cleaning process in which this mineral matter is removed from mined coal to produce a cleaner product.

During washing, the coal is also sized and blended to meet customer specifications. Coal washing increases the heating value and the quality of the coal, by lowering the level of sulphur and mineral constituents. The coal preparation process involves characterisation, liberation, separation and disposition.

Characterisation identifies the composition of the different raw coal particles. Liberation involves crushing the mined coal and reducing it to very fine particles. Separation is the partitioning of the individual particles into their appropriate size groupings and separating the mineral matter particles from the coal. Finally the disposition stage involves the dewatering and storage of the cleaned coal and the disposal of the mineral matter (WCI, 2007).

During various operations in coal washeries, a lot of particulate matters and gaseous pollutants are generated causing a serious air pollution problem in the area. Coal washeries release large amounts of solid and liquid waste causing serious environmental problems. The washeries reduce the ash content of coal to 17.5% or less (Komnitsa *et al*, 2001). This process consumes clear water in the range of 0.2 to 0.25 m^3/tonne of raw coal input. The washeries are operated in the closed water circuit system but still about 12-18% of raw water is discharged as effluent.

2.2.2 Efficient Combustion Technologies (During Combustion)

In this section technologies which improve the efficiency with which coal is burnt are discussed with particular emphasis on operating parameters, process and thermal efficiency. Typical thermal efficiencies were provided. These technologies include:

- Pulverised Coal Combustion
- Fluidised Bed Combustion
- Integrated Gasification Combined Cycle
- Pressurised Pulverised Coal Combustion
- Supercritical & Ultra supercritical Technology
- Underground Coal Gasification

Information in this section was sourced mostly from the WCI (2007) with some key ideas from other authors. For further information, the WCI may be consulted.

2.2.2.1 Pulverised Coal Combustion

Conventional coal-fired generation today is normally via the route of PCC. PCC can be used to fire a wide variety of coals, although it is not always appropriate for those with high ash content. In PCC power stations, coal is first pulverised then blown into a furnace where it is combusted at high temperature. The resulting heat is used to generate steam, which drives a steam turbine and generator. Efficiencies have been steadily rising with emissions reduced per kW of electricity generated. This trend continues as technologies advance. This technology is discussed in more detail in Section 2.3. Major environmental impacts relate to air pollution through emissions and surface and ground water pollution through water utilisation and treatment.

2.2.2.2 Fluidised Bed Combustion

In fluidised bed combustion (FBC), coal is burned in a reactor comprised of a bed through which gas is fed to keep the fuel in a fluidised state. This improves combustion, heat transfer and recovery of waste products.

According Johnsson (2001) and Armesto *et al*, (2003), the higher heat exchanger efficiencies and better mixing of FBC systems allows them to operate at lower temperatures than conventional (pulverised) coal-burning systems. By elevating pressures within a bed, a high-pressure gas stream can be used to drive a gas turbine, generating electricity. FBC technologies include atmospheric pressure fluidised bed combustion in both bubbling (BFBC) and circulating (CFBC) beds, pressurised fluidised bed combustion (PFBC), whilst pressurised circulating fluidised bed combustion (PCFBC) is being demonstrated (WCI, 2007).

- *Circulating Fluidised Bed Combustion* (CFBC) has been most widely used. An extensive operating history exists for this technology (WCI, 2007). CFBC uses the same thermodynamic cycle as PCC and therefore its power generation efficiency is in the same range, which is normally between 38% and 40%. Circulating fluidised-bed boilers operate at lower temperatures, ranging from 850°C to 900°C, thereby suppressing thermal Nitrogen dioxides emissions as the generation of nitrogen dioxides is dependent upon the combustion temperature.

- *Pressurised Fluidised Bed Combustion* (PFBC) is based on the combustion of coal under pressure in a deep bubbling fluidised bed at 850°C. Depending on the velocity of the air through the fluidised bed, two PFBC variants exist – bubbling bed PFBC (lower velocities) and circulating bed PFBC (higher velocities). PFBC units are intended to give an efficiency value of over 40%, and low emissions. Developments of the system using more advanced cycles are intended to achieve efficiencies of over 45% (WCI, 2007).

For more detail on these processes, Bonn and Richter, (1990), further discusses aspects of coal combustion in atmospheric and pressurised fluidised beds.

2.2.2.3 Integrated Gasification Combined Cycle

In IGCC systems, coal is not combusted directly, but reacted with oxygen and steam to produce a ‘syngas’ composed mainly of hydrogen and carbon monoxide. The syngas is cleaned of impurities and then burned in a gas turbine to generate electricity and to produce steam for a steam power cycle (WCI, 2007). A more detailed discussion of this technology follows in Section 2.5.

2.2.2.4 Pressurised Pulverised Coal Combustion

Pressurised pulverised combustion of coal (PPCC) is a technology currently under development, mainly in Germany. It is similar to conventional pulverised coal combustion, in that it is based on the combustion of a finely ground cloud of coal particles, the heat released from combustion generates high pressure and temperature steam which is used in steam turbine-generators to produce electricity. The pressurised flue gases exit the boiler and are expanded through a gas turbine to generate further electricity and to drive the gas turbine’s compressor; hence this is a form of combined cycle power generation (WCI, 2007). Foster, (2007), also describes the technology as a coal-based combined-cycle. Foster further mentioned that this process can be considered as the most suitable and straightforward design to utilise hard coal in a combined cycle with an efficiency of ~55% and above.

2.2.2.5 Supercritical & Ultra supercritical Technology

Supercritical combustion is a thermodynamic expression describing the state of a substance where there is no clear distinction between the liquid and the gaseous phase. The cycle medium is a single phase fluid with homogeneous properties and there is no need to separate steam from water. Once through boilers are therefore used in supercritical cycles. Supercritical plants offer higher efficiencies than conventional, sub-critical plant. Ultra supercritical plants operate at very high temperatures and pressures and have the potential to offer efficiencies of over 50% (WCI, 2007). Both Hack *et al*, (2008) and Fan, *et al* (2008), stated that development work is under way to offer circulating fluidized bed technology up to 800 MWe capacities with ultra-supercritical steam parameters. Simultaneously, the technology to provide capability for air and oxy-combustion flexible operation to allow carbon capture is being developed. The proven high-efficiency circulating fluidized-bed technology offers a good solution for carbon dioxide reduction for both repowering of existing coal-fired power plants and in greenfield power plants.

2.2.2.6 Underground Coal Gasification

Although the technology was pioneered in the late 1800’s, interest in UCG surged again in the recent years. Unlike all major UCG programs of the 20th century, this increased interest is mainly stimulated by private capital in response to record-high oil and energy prices. As result of this surge, knowledge of UCG is sought again and more than 30 trials are conducted or planned in Australia, China, India, South Africa, New Zealand, Canada and the USA. Many of these trials are carried out under technological auspices of Ergo-Exergy - the leading supplier of modern commercial UCG technology and the holder of proprietary rights for the process called eUCG (Klimenko, 2009).

In the UCG process, water/steam and air or oxygen are injected into a coal seam. The injected gases react with coal to form a combustible gas which is brought to the surface and cleaned prior to utilisation. This technology is being used to exploit coal seams that are otherwise impossible to mine. While efficiency improvements and advanced combustion technologies tend to reduce all polluting emissions, the opposite may not be true: the removal of local pollutants has energy cost and thus tends to slightly increase carbon dioxide emissions (Zheng *et al*, 2003). Both Shu-qin and Jun-hua, (2002) suggested that environmental benefits of underground coal gasification far outway the negatives.

2.2.3 Technologies for Reducing Emissions of Pollutants (Post Combustion)

In this section technologies deployed to reduce emissions from the combustion of coal are discussed. These are post combustion technologies. Most of the information in this section was sourced from the WCI supplemented with key ideas and comments from other authors. The literature reviewed suggests that there are number of ways in which emissions of pollutants are reduced post combustion. Different methods or technologies typically remove specific pollutants. The WCI (2007) identified the following methods:

- Electrostatic precipitators
- Fabric filters
- Hot gas filtration systems
- Wet particle scrubbers
- Activated carbon injection
- Six main categories of Flue gas desulphurization
- Selective and non-selective catalytic reduction

Particulates in the flue gas must be managed. For this purpose, electrostatic precipitators are the most widely used particulate emissions control technology in coal-fired power generating facilities. Particulate/dust laden flue gases are passed horizontally between collecting plates, where an electrical field creates a charge on the particles. The particles are then attracted towards the collecting plates, where they accumulate. In dry electrostatic precipitators the agglomerated particles are then removed in a dry form by mechanical rapping or vibration to create a powder for disposal. In wet electrostatic precipitators the particles are sprayed and washed off as a slurry (WCI, 2007). According to Turner, *et al,* (2005), these devices are also known as Plate-wire electrostatic precipitators. He further mentions that the voltage applied to the electrodes causes the air between the electrodes to break down electrically, an action known as a "corona". The electrodes usually are given a negative polarity because a negative corona supports a higher voltage than a positive corona before sparking occurs. The ions generated in the corona follow electric field lines from the wires to the collecting plates. Therefore, each wire establishes a charging zone through which the particles must pass.

A less widely used technology involves fabric filters, also known as baghouses, to collect particulates from the flue gas on a tightly woven fabric by sieving and other mechanisms. The choice between electrostatic separation and fabric filtration depends on coal type, plant size, and boiler type and configuration. Fabric filters are useful for collecting particles with resistivities either too low or too high for collection with electrostatic precipitators.

Similarly, hot gas filtration systems operate at higher temperatures (500-1000°C) and pressures (1 – 2 MPa) than conventional particulate removal technologies, eliminating the need for cooling of the gas. Particulates and contaminants such as sulfur, alkali metals and heavy metals have to be removed by the filter. A range of technologies such as cyclones, ceramic barrier filters, high-temperature fabric filters, granular bed filters and high-temperature ESP's have been under development for many years. Some of these are in the demonstration stage but further development is needed to enable commercial exploitation (WCI, 2007). Turner and McKenna, (1984) and Turner, (1998) states that Fabric filters are used where high-efficiency particle collection is required. Limitations are imposed by gas characteristics (temperature and corrosivity) and particle characteristics (primarily stickiness) that affect the fabric or its operation and that cannot be economically accommodated.

Wet particle scrubbers for particulate control are used in a limited number of coal-fired plants, with most of these installations located in the USA, to capture fly ash in addition to sulphur dioxide. Water is injected into the flue gas stream to form droplets. The fly ash particles impact with the droplets forming a wet by-product, which then requires disposal. Wet particle scrubbers have a removal efficiency of 90-99.9% (WCI, 2007).

Activated carbon injection involves injecting powdered activated carbon into the flue gas stream exiting the boiler and absorbing pollutants such as mercury onto particulate matter, which is then removed in existing particulate control equipment. Mercury may be adsorbed onto the surface of activated carbon by a combination of adsorption, condensation, diffusion and chemical reactions (Uberoi and Shadman, 1991).

The efficiency of activated carbon depends upon the type of activated carbon, the mercury speciation and the temperature process conditions. Activated carbon is expensive, has a poor capacity, a low applicable temperature range, and has slow regeneration and adsorption rates (Lee *et al*, 2001).

To remove sulphur, a technology called Flue Gas Desulphurisation (FGD) is used. FGD technologies can be classified into six main categories: wet scrubbers; spray dry scrubbers; sorbent injection processes; dry scrubbers; regenerable processes; and combined sulphur dioxide/nitrogen oxides removal processes. Soud (2000) also mentions theses six processes. Wet scrubbers tend to dominate the global FGD market. The technology uses an alkaline sorbent slurry, which is predominantly lime or limestone based. A 'scrubbing vessel' or scrubber is located downstream of the boiler and flue gas cleaning plant, in which the sulphur dioxide in the flue gases reacts with the limestone sludge, forming gypsum. Interestingly, physical deterioration of a working FGD plant results from the harsh acidic conditions in which the system operates. Dill and Ridge (1996) mentions that the mixture of calcium and sulphur in addition to chlorides, fluorides, manganese and many other elements in the coal compound plant operational problems. Zones with unique corrosive environments in the system include the scrubber inlet ducts, the absorber tower, the scrubber outlet ducts, the bypassed/scrubbed flue-gas mixing chamber and the exit stack. If a FGD system is not maintained regularly, Dille and Ridge, (1996) envisaged a future where an FGD system could potentially contribute to unit derates and even be the sole cause for unscheduled outages.

Flue-gas treatment technologies provide alternatives for nitrogen dioxides control at coal-fired power plants. The systems are installed downstream of the furnace to remove the nitrogen dioxides from the flue gases, following its formation. These technologies commonly involve the injection of ammonia, urea or other chemical reagents, which react with the nitrogen dioxides in flue gases to convert it to molecular nitrogen or nitrates (Buschmann, 2002). These include among other technologies

- Selective catalytic reduction (SCR)
- Selective non-catalytic reduction (SNCR)

In SCR for the removal of nitrogen oxides, ammonia vapour is used as the reducing agent and is injected into the flue gas stream, passing over a catalyst. The optimum temperature is usually between 300°C and 400°C. The key difference between SCR and SNCR is the presence in SCR systems of a catalyst, which accelerates the chemical reactions. The catalyst is needed because SCR systems operate at much lower temperatures than SNCR; typical temperatures for SNCR are 870-1200°C. The Nitrogen oxide removal efficiency for existing SCR installations ranges between 50 and 90% while the removal efficiency of SNCR systems is 15-45%. (IEA Coal Research, 2004).

2.3 Conventional Pulverised Coal-Fired Electricity Generation

As mentioned above, PCC is one in a suite of CCT's. The technology will be discussed in more detail in this section with particular emphasis on the typical operating parameters, and efficiencies. PCC is the most commonly used method to generate power in coal-fired plants, and is based on many decades of experience. Units operate at close to atmospheric pressure, simplifying the passage of materials through the plant. Figure 3 below illustrates the basic process. Modern PCC technology is well developed, with thousands of units around the world, accounting for well over 90% of coal-fired capacity (IEA CCC 2004). In South Africa, the majority of electricity is generated in these types of plants. All plants currently in use utilise sub-critical boilers (the steam pressure is below the critical pressure of water – approximately 218 atmospheres). (Haw and Hughes, 2007).

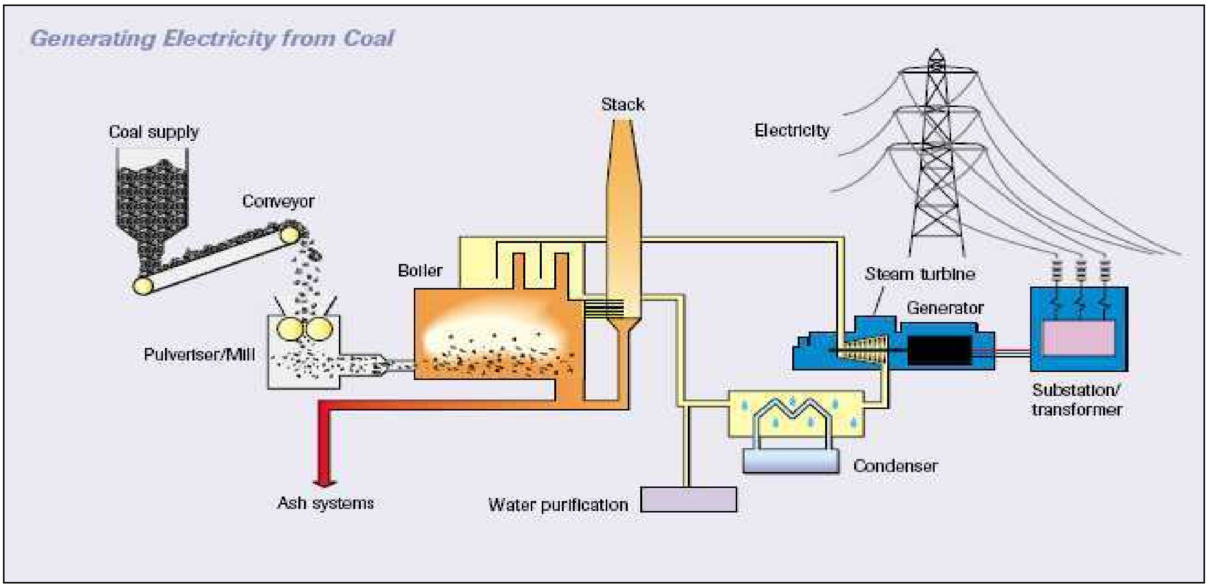


Figure 3: Generating Electricity from Coal (WCI, 2007).

In PCC coal is ground (pulverised) to a fine powder, so that less than 2% is +300 µm and 70-75% is below 75 µm, for a bituminous coal. The pulverised coal is blown with part of the combustion air into the boiler plant through a series of burner nozzles. Secondary and tertiary air may also be added.

Combustion takes place at temperatures between 1300-1700°C, depending largely on coal rank. Steam is generated, driving a steam generator and turbine. Particle residence time in the boiler is typically 2-5 seconds, and the particles must be small enough for complete burnout to have taken place during this time.

Two broadly different boiler designs are used. One is the traditional two-pass layout where there is a furnace chamber, topped by some heat transfer tubing to reduce the furnace exit gas temperature (FEGT). The flue gases then turn through 180°, and pass downwards through the main heat transfer and economiser sections. The other design is to use a tower boiler, where virtually all the heat transfer sections are mounted vertically above each other, over the combustion chamber (IEA CCC 2004).

PCC boilers have been built to match steam turbines which have outputs between 50 and 1300 MWe. In order to take advantage of the economies of scale, most new units are rated at over 300 MWe, but there are relatively few really large ones with outputs from a single boiler/turbine combination of over 700 MWe. This is because of the substantial effects such units have on the distribution system if they should 'trip out' for any reason, or be unexpectedly shut down.

One of the driving forces which is currently encouraging the use of more efficient power plant is the environmental concern in many countries, and the declared goal of most OECD (Organisation for Economic Co-operation and Development) governments to reduce carbon dioxide emissions to 1990 levels. This is a goal which leaves power generators with many unsolved problems, but increasing the thermal efficiency of converting coal to power is one of the less expensive ways of reducing carbon dioxide emissions. It does, however, involve the construction of new boilers and turbines, as the costs for retrofitting a supercritical steam system to an existing sub critical boiler would be prohibitive.

Increasing thermal efficiency has the potential for reducing other emissions per MWe generated, such as those of sulphur dioxide and nitrogen dioxides. Where the coal cost is high which is typically low ash coal, as where traded coals are used, increasing thermal efficiency can result in reduced overall costs in new plants for power generation, as less fuel is needed.

The overall thermal efficiency of some older, smaller units burning possibly, poor quality coals, can be as low as 30%. A commonly used assumption for the average efficiency of larger existing plants with sub critical steam burning somewhat higher quality coals is that it is in the region of 35-36%.

New plants, however, with supercritical steam can now achieve overall thermal efficiencies in the 43-45% range (IEA CCC 2004).

Various measures can be used to increase the thermal efficiency relative to current design practice. Logan and Nah, (2002), Scheffknecht *et al*, (2003) and Siemens, (2004) all mentioned measures outlined below. It must however be noted that the actual temperatures and efficiencies were sourced from the (IEA CCC 2004).

- reducing the excess air ratio from 25% to 15% can cause a small increase in efficiency
- reducing the stack gas exit temperature by 10°C (while recovering the heat involved) can bring about a similar increase;
- increasing the steam pressure and temperature from 25 MPa/540°C to 30 MPa/600°C can increase efficiency by nearly 2 percentage points;
- using a second reheat stage can add another 1% of efficiency
- The condenser pressure can further increase efficiency by halving it

As with all technical options, there is a trade-off between the costs involved (both capital and operating), the risk element in the decision and the amount of additional energy recovered.

2.4 Gasification

Another key technology to this research is the gasification of coal. Particular emphasis has been placed on this technology as it is an important enabling component of both the IGCC and UCG processes. This section provides an overview of the fundamentals of the gasification processes.

Gasification refers to the reaction of coal with air or oxygen and steam to yield a gaseous product, a synthesis gas or `syngas', for use directly as a fuel, or as a feed to synthesise other gaseous or liquid fuels or chemicals. Gasification is, in fact, the incomplete combustion of coal. Although the chemical and physical processes are similar in coal gasification and combustion, the pollutant-formation processes are different. The main difference is the reducing atmosphere in gasification whereby sulphur from the coal is converted mostly to hydrogen sulphide (H_2S) rather than to sulphur dioxide, whilst nitrogen from the coal is converted to ammonia (NH_3) rather than to oxides of nitrogen (IEA CCC, 2003).

The syngas produced by steam-oxygen coal gasification consists principally of hydrogen, carbon monoxide, methane, carbon dioxide and unreacted steam. The gas will also be diluted with nitrogen when air is used as the oxygen source. According to Engelbrecht *et al*, (2007), the gasification reactions (1 and 2) occur at a much lower rate (up to 1000 times slower) than the combustion reaction (3):

$C + CO2 \rightarrow 2CO$ (1)
$C + H2O \rightarrow CO + H2$ (2)
$C+ O2 \rightarrow CO2$ (3)

The rate of the gasification reactions therefore has a major effect on the carbon conversion efficiency that can be achieved in a fluidised bed gasifier which operates at moderate temperatures (< 1000°C).

Adams *et al*, 2003 states that gasification can be employed for the conversion of a wide range of coals, from anthracite and low-volatile coals to sub bituminous, high-volatile coals and lignite, by choosing and developing the gasification process that best suits the properties of the coal.

Three gasifier formats or processes are possible, with fixed beds (not normally used for power generation), fluidised beds and entrained flow. The gasification efficiency of the fluidised bed gasifier is 55% - 75%, while the entrained flow carbon efficiency is 55% - 70% (Engelbrecht *et al*, 2007)

Coal contains a large number of components in addition to carbon. These also react or vaporise during gasification so that by products appear in the raw gas, often as undesirable contaminants. The volatile matter in coal can appear in the gas as tars, oil, naphtha, phenols, cresols and other compounds. Coal also contains other reactive or easily vaporised elements such as beryllium, arsenic, selenium, cadmium, mercury and lead.

Gasification technologies are increasingly being developed to provide environmentally clean and efficient power generation from a range of fuels such as coal, biomass and oil residues. In this context, they can be used in IGCC systems, the CCT that will be discussed in the next section. As discussed above, IGCC technology has the potential to provide high efficiencies and low environmental emissions by combining gas-and steam-turbine power-generation technologies (IEA CCC, 2003).

2.5 Integrated Gasification Combined Cycle (IGCC)

As mentioned above, the source of the syngas for the IGCC process is derived from the gasification process. This process has been identified as a highly advanced technology which offers improved technical and environmental performance. This section describes the IGCC process and the typical efficiencies relating to its deployment.

IGCC uses a combined cycle format with a gas turbine driven by the combusted syngas, while the exhaust gases are heat exchanged with water/steam to generate superheated steam to drive a steam turbine as seen in Figure 4 below. Using IGCC, more of the power comes from the gas turbine. Typically 60-70% of the power comes from the gas turbine with IGCC, compared with about 20% using Pressurised Fluidised Bed Combustion (PFBC).

IGCC technology offers high efficiency levels, typically in the mid-40%'s (IEA CCC 2003). Although plant designs offering close to 50% efficiencies are available, as much as 95-99% of nitrogen dioxides and sulphur dioxides emissions are removed (IEA CCC 2003).The further development and support of IGCC offers the prospect of net efficiencies of 56% in the future, and therefore its widening deployment will have an increasingly favourable impact on the environmental performance of coal (IEA CCC 2003). Similar figure were also reported by both Bressan *et al*, (1997) and Higman *et al*, (2003).

IGCC plants can be configured to facilitate carbon dioxide capture. The new gas is quenched and cleaned. The syngas is 'shifted' using steam to convert carbon monoxide to carbon dioxide, which is then separated for possible long-term sequestration (IEA CCC 2003).

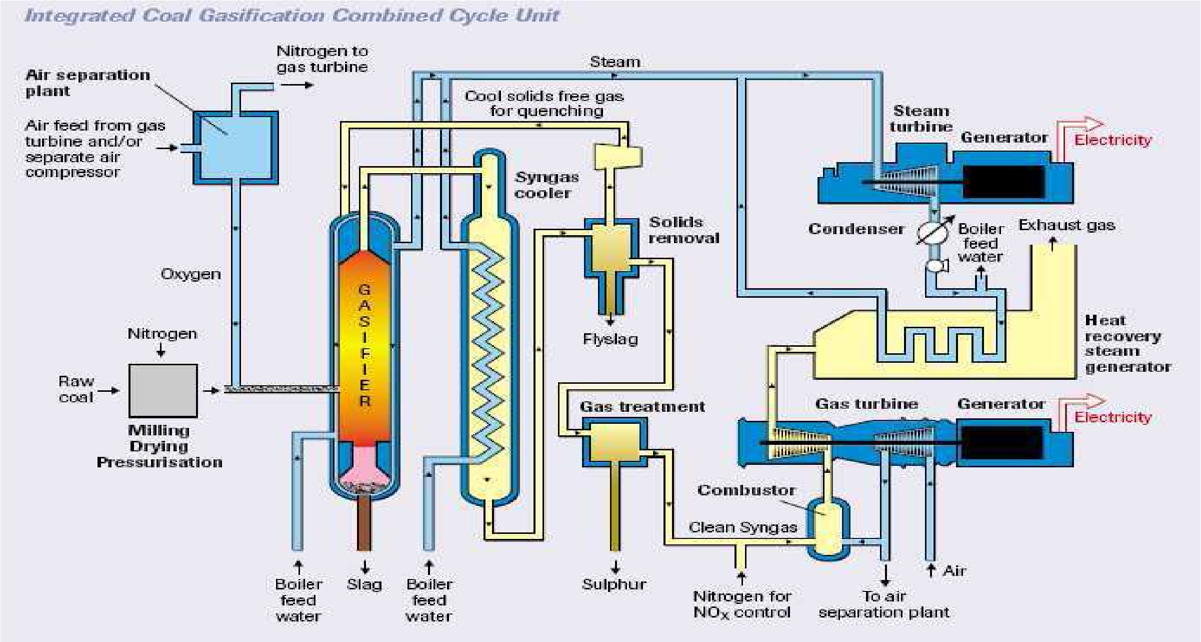


Figure 4: An Integrated Gasification Combined Cycle Unit (WCI, 2007).

2.6 Underground Coal Gasification (UCG)

Another technology key to this research is the UCG process. This technology is also enabled through the process of gasification as described above. In this section, the history, process, potential and merits of UCG is discussed.

UCG permits coal to be gasified *in situ* within the coal seam, via a matrix of wells. The coal is ignited and air is injected underground to sustain a fire, which is essentially used to "mine" the coal and produce a combustible synthetic gas (Walker 1999). Ökten and Didari, (1994), also describe the technology as in situ gasification. This can be used as a fuel for power generation. This process avoids the need for coal mining, transportation, preparation, the gasifier equipment, and the transportation and disposal of ash. These all have cost labour and environmental benefits.

An underground cavity is created as the coal burns, and the boundaries of the cavern form the walls of an underground reactor. The reactor is able to operate at high pressures (related to its depth) and temperatures. UCG has the potential to extract coal resources previously regarded as either uneconomic or inaccessible due to depth, seam thickness, seam slope, seam fracturing and displacement, or other mining and safety considerations. A simplistic illustration of the underground coal gasification process is given in Figure 5 below.

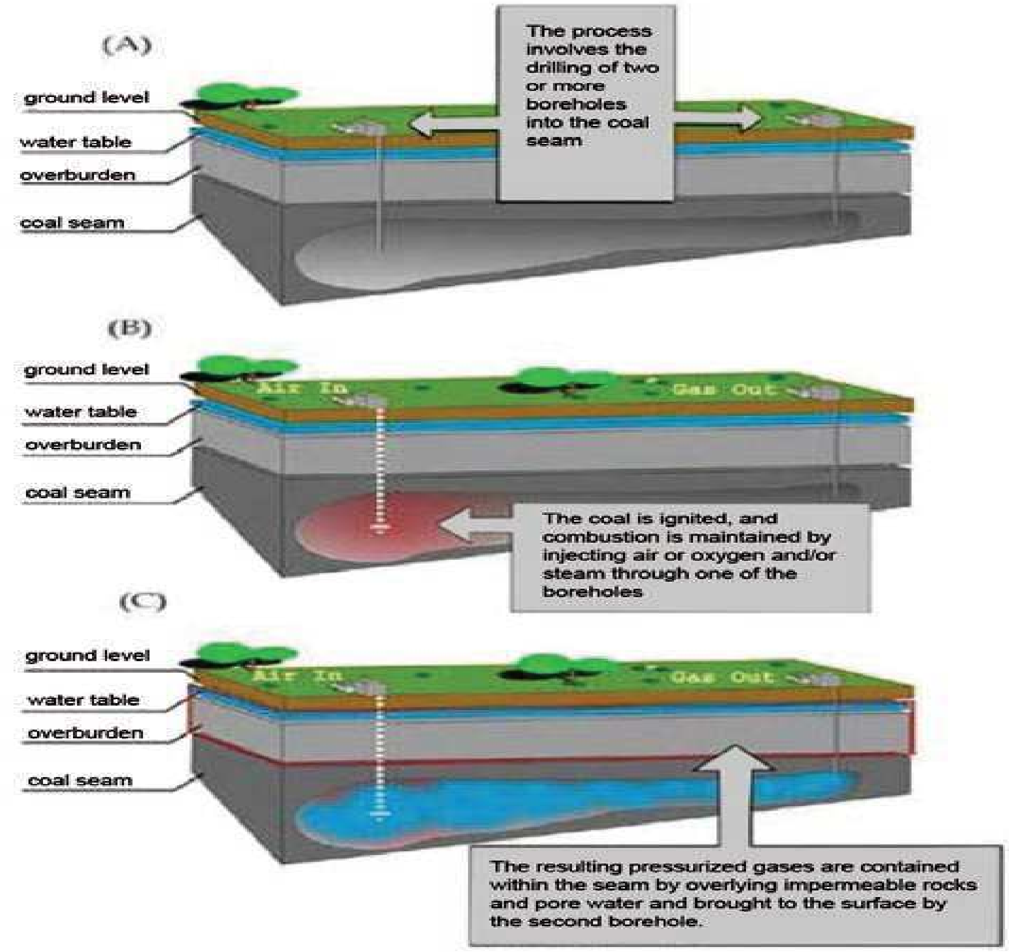


Figure 5: UCG Process (Ergo Exergy, 2005).

UCG consumes water in the gasification process, to produce hydrogen. This does entail consumption of the water in the coal seam, and in the immediate surrounding strata. The underground aquifers are closely monitored to ensure no impact on aquifers closer to the surface that may be in use for domestic or agricultural purposes, or may evacuate into surface streams. Apart from the usage aspect, there is also a risk of contamination of aquifers and water bodies with UCG products. This risk is mitigated by maintaining a negative hydraulic gradient into the underground cavity thereby forcing removal of UCG products with the water influx (Blinderman & Fidler, 2003).

Olness and Gregg, (1977) provides a historical account of the technology's development. They also mention that it has been researched over the past 70 years, and has been in commercial operation for more than 50 years in the former Soviet Union. The gas was used there for heating and power generation. Although strictly speaking this technology is commercially mature, it is fair to say that this former Soviet Union technology is only now emerging in the Western World with the first pilot plant having operated for four years in Australia and the Eskom pilot plant having just started up in January 2007. Rogul, (2008), also notes this in his review of Russian and European UCG. There are many other commercial projects either entering pilot plant phase or still undergoing study, in Australia, New Zealand, USA, India, Pakistan, Canada and Italy.

There are many emerging factors that give a new impetus to the commercialisation of UCG technology, both internationally and locally. These include an increasing need to reduce emissions from coal-fired power plant; a desire to find alternatives to natural gas as a fuel due to high prices and availability; and a reviving interest in synthetic fuels as a result of high and unstable oil prices. Shafirovich *et al*, (2009) has similar views on UCG.

Van der Riet, (2008), states that UCG has synergies with conventional mining through the ability to exploit coal reserves that would not normally be mined. He also notes that this could increase South Africa's coal resources dramatically. It is estimated that there is a conservative potential for 350 GW of electricity capacity, based on UCG within South Africa. This effectively increases South Africa's coal resources. The Eskom resources and strategy and generation divisions have estimated that there is an additional 45-billion tons of coal (excluding coalfields in KwaZulu-Natal, Ermelo and Witbank) suitable for UCG. The above mentioned potential could be realised if UCG is deployed together with IGCC technology with 50% efficiency and 25 year plant life.

Van der Riet *et al* (2007) explains that Eskom is developing UCG production to initially co-fire the gas with coal in Majuba power station, and to explore options for supplying gas for a new high efficiency power station. A conceptual and scoping study was completed in November 2002, which showed significant potential of UCG for South Africa.

UCG is ideally suited for complete extraction of both the solid and gaseous fuels, from coal resources that are not destined for conventional mining to extract solid fuel. (Van der Riet, 2008). Eskom has determined that UCG technology offers the following merits.

- UCG technology, in combination with a combined cycle power station, significantly reduces the emissions footprint of a coal-fired power station.

- The overall resource utilisation efficiency is very high, especially when the gas is used for power generation in a combined cycle power station. UCG as a mining technology also effectively extends South Africa's coal reserves, by allowing extraction of coal previously disregarded a being unminable.

- The focus on "unminable" resources suggests minimal overlap with existing conventionally mining houses, although conflict is possible with Coal Bed Methane (CBM) developers.

- The broader geographic availability of coal suitable for UCG enables Eskom to position new coal generating plant far more strategically, to support demand side needs and stabilise the transmission network.

- The technology will increase Eskom operational flexibility and efficiency, by allowing the coal mine and power station to effectively integrate.

- The technology, on a large scale, offers the opportunity to reduce the cost of electricity from new coal-based power stations. It achieves this through an inherently simpler mining process, and a shorter resource-to-electricity production supply chain.

- The UCG technology is modular, and Eskom has already pioneered the basis of the first module. The modularity, availability and relative simplicity of major plant components enables faster lead times than for conventional coal plant.

2.7 UCG-IGCC

After discussions relating to gasification, UCG and IGCC technology, UCG-IGCC will now be discussed which is the application of both these technologies put together. In this section, the technology, process and typical operating efficiencies in comparison to other technologies discussed above are explored.

The most efficient and cost-effective way to generate electricity from UCG gas is via the use of a gas turbine combined-cycle plant. The gas turbine can provide some or all of the compressed air needed by the UCG process, and achieve higher power outputs on the UCG gas than on natural gas (NG). An IGCC plant using UCG for gas production is called an UCG-IGCC plant. Figure 6 below illustrates the UCG-IGCC process (Ergo exergy, 2005).

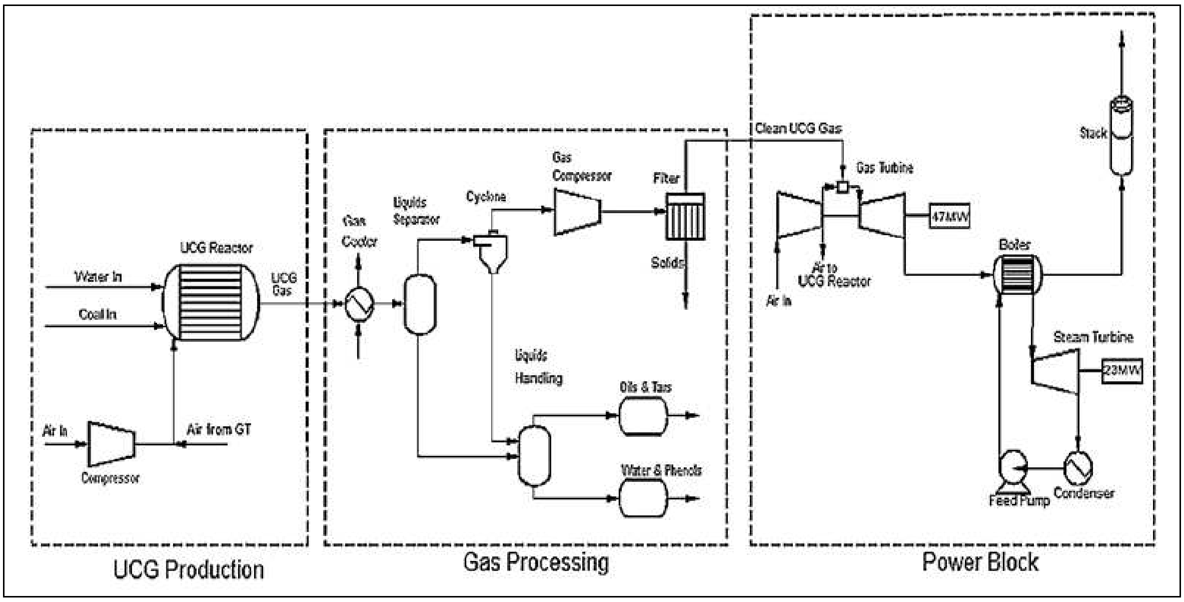


Figure 6: The UCG-IGCC Process (Ergo Exergy, 2005).

The typical environmental performance of current and future fossil-fuel power generating options is described in Figure 7 (BHP Billiton, 2002). Natural gas combined cycle is taken as the baseline for all fossil fuelled stations. The figure shows how UCG-IGCC is the closest coal fired plant to achieving the emissions of a natural gas plant. The ultra-supercritical pulverized fuel plant is still under development, and could potentially be a cleaner coal option than UCG-IGCC once commercially available.

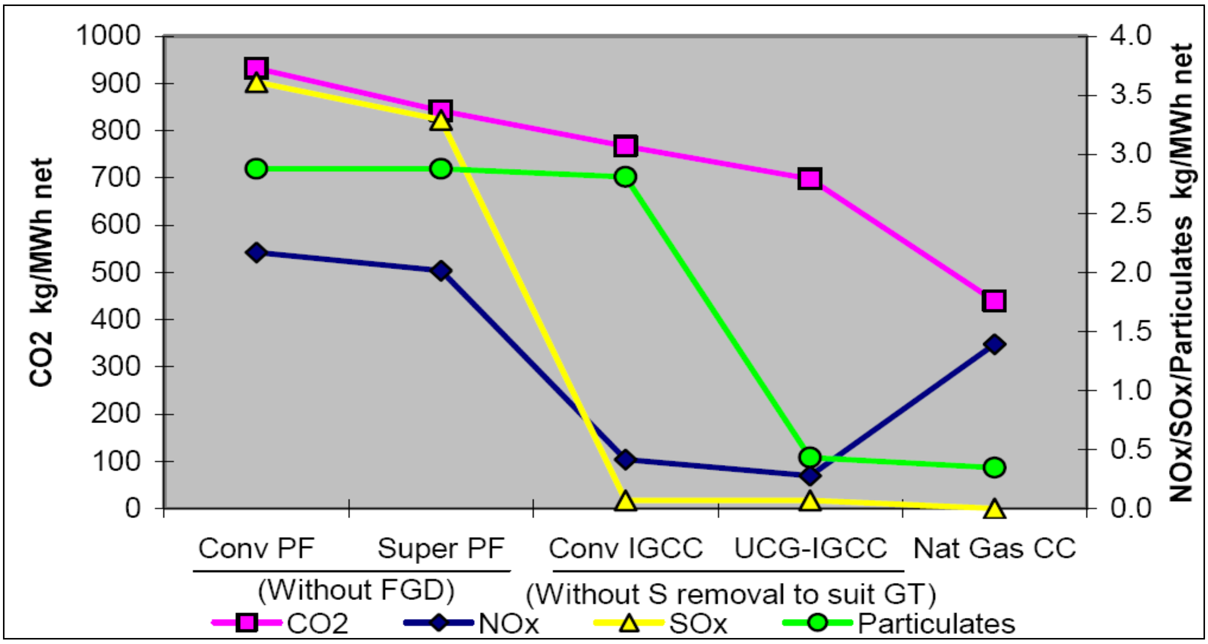


Figure 7: The typical environmental performance of current and future fossil-fuel power generating (BHP Billiton, 2002).

As seen below in Figure 8, UCG-IGCC demonstrates carbon dioxide emissions of about 25% lower than a supercritical boiler plant. At 673 kg/MWh, these emissions are still higher than the emissions of a combined-cycle gas turbine fuelled by natural gas. However, the UCG-IGCC with carbon dioxide sequestration produces only 333 kg/MWh, providing significant reduction against the NGCC plant (Ergo exergy, 2005).

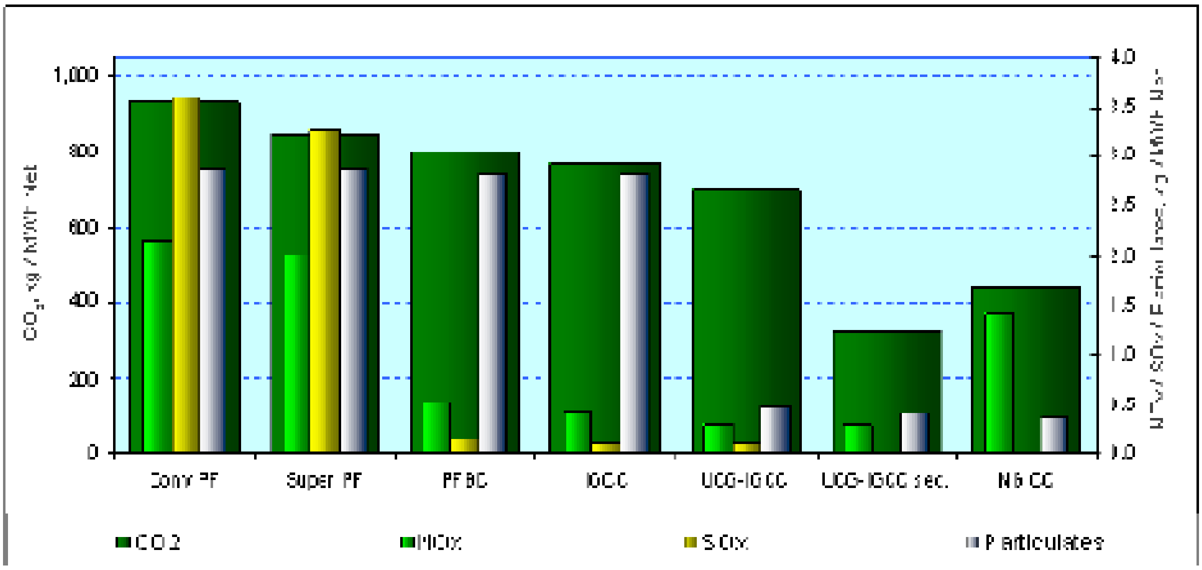


Figure 8: Air Emissions from Conventional Fossil Fuel Power Plants and UCG-IGCC (Ergo Exergy, 2005).

A UCG-IGCC power plant will generate electricity at a much lower cost than an existing or proposed fossil fuel power plant. The UCG overall chemical efficiency is typically 75%, but the recovery is over 95% as the entire coal seam, including any methane gas and combustible roof, floor and partings, will be consumed in the process. Figure 9 below illustrates relative utilisation efficiencies for the current scenario of power stations with an associated underground coal mine.

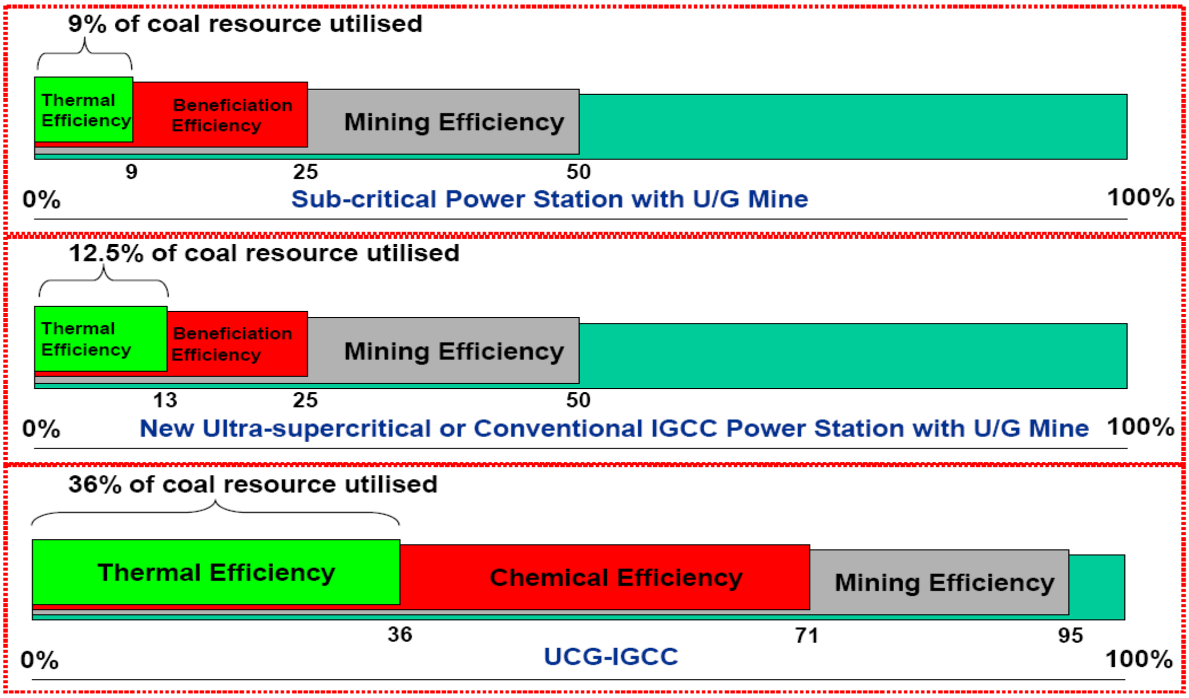


Figure 9: Resource utilisation efficiency for (a) a current, high efficiency longwall mining operation with a conventional sub-critical pulverised fuel power station; (b) a underground coal gasification (UCG) mining operation integrated with a combined cycle power station; (c) a coal bed methane (CBM) mining operation integrated with a combined cycle power station. (Van Der Riet, 2007).

Simply put, UCG gas is an ideal fuel for power generation in Gas Turbine Combined Cycle (GTCC) configuration because:

- It gives a 25% increase in the gas turbine power output compared to natural gas.
- It produces fewer air emissions: greenhouse gas emissions it can be as much as 30% less than natural gas.
- The cost of electricity produced from UCG gas is much less than with natural gas.
- UCG gas can be produced in abundance for years to come and used to fuel GTCC plants in areas without any natural gas supply.

2.8 Summary of Literature Review

Chapter 2 provided an overall and fundamental understanding of LCA as well as CCT's being deployed around the world with a description of their processes and typical operating efficiencies. In turn, this has provided the background required to understand the key technologies and variables which form part of the LCA. From the review it is clear that a defined methodology exist to conduct LCA's with the capacity to yield good scientific results. The review also highlights the multitude of technologies which exist to improve the technical and environmental performance of coal as primary source of fuel for electricity generation.

CHAPTER 3: METHODOLOGY

Having reviewed the pertinent literature relating to the research, in this chapter, the methodology with which the LCA was executed is discussed. The pertinent information presented relates to the 4 stage approach as outlined in the ISO guidelines for LCA as discussed in Section 2.1. Very importantly, it also describes the basis for comparison of the PCC and UCG-IGCC technologies.

The approach that was followed included:

1. Establishing the goal and scope of each study. Care was taken to ensure that system boundaries were chosen which enable a fair comparison between the different combinations of technology.

2. An inventory analysis. This involved accounting for all significant inputs and outputs of the system

3. Performing an assessment of the impacts. This was done by direct comparison of the inventory values and impact categories.

4. Using the analysis to identify improvement opportunities.

3.1 Basis for Comparison

As the LCA involved a comparative assessment of two different technologies, it was necessary to establish the basis for comparison of the two.

For this LCA, the “life cycle” was defined as the system to produce 1 MW of electricity. This is known as the functional unit. This was applicable to both PCC and UCG-IGCC technologies.

After failed attempts at obtaining credible LCA software for the research, the focus was on obtaining realistic inventory values for all significant inputs and outputs of the system. It was therefore necessary to utilize information from a related study conducted by BHP Billiton, 2002. Furthermore, because of the lack of information and data relating to a new technology such as UCG-IGCC, it was necessary to restrict the examination of the environmental variables to a select few as detailed in the impact assessment section. This consisted of aggregating each stressor (*e.g.* carbon dioxide, sulphur dioxides, nitrogen dioxides, SPM, solid waste, fresh water and resource consumption) into an impact category (*e.g.* GGE and resource energy).

3.2 System Boundaries

Another key parameter identified was the system boundaries for both the PCC and UCG-IGCC technologies. This was also particularly important for comparative purposes. System boundaries were set as wide as possible, up to the production of the first common product for each technology which is 1MW. Decommissioning, repairs and maintenance were excluded from the present analysis.

The report does not look at environmental stressors impacting beyond the boundaries of the plant which could lead to cumulative impacts in the receiving environment over time. The inclusion of these would result in too many unknown variables and would hence compromise the data integrity. This would be an important addition in a more detailed future study.

3.3 Data Accuracy

As mentioned above, after failed attempts at obtaining credible LCA software for the research, the focus was on obtaining realistic inventory values for all significant inputs and outputs of the system. Due to costs involved, it was therefore necessary to utilize information from a related study conducted by BHP Billiton (2002).

Data relating to two case studies with particular reference to PCC and UCG-IGCC technologies required data checking for a large number of energy and materials flows for the numerous unit processes comprising the process chain and life cycle stages (Wibberly, 2001). The study used the BHP LCA model EMMA (Eco-model for Materials and Manufacturing Assessment). EMMA has been developed over the last eight years and is the result of extensive effort at BHP Research. In particular, the model contains a comprehensive data set for Australian energy and materials. EMMA also has unique features to enable in-depth analysis of processing chains (e.g. seven categories for carbon emissions, automatic sensitivity analysis) (Wibberly, 2001).

Every effort has thus been taken to ensure correct, representative and best available data. Due to the UCG-IGCC technology being an emerging technology, it was not possible to obtain site-specific data. The case study was therefore based on a hypothetical installation at specific location, both for data compatibility and to ensure that the study was carried out in an appropriate context. The analysis was performed for all goods and services involved in each case study. The results of related LCAs were used for benchmarking.

3.4 Transparency

A key requirement of LCA is transparency in methodology, data sources, estimates and assumptions.
The following information is included for both PCC and UCG-IGCC:

- Scope for each analysis.
- Technology overview and key specifications for the individual case study.
- Location - assumed or actual.
- Functional unit
- Construction, including sources and transportation of key materials. This stage in the life cycle generally has a negligible impact on the LCA values with the exceptions being photovoltaics, wind and hydroelectricity (Wibberly, 2001).
- Utilisation, including the provision of energy, raw materials and externalities
- Waste management.

3.5 Impact Assessment

As mentioned above because of the lack of information and data relating to a new technology such as UCG-IGCC, it was necessary to restrict the examination of the environmental variables to a select few. The impact assessment was used to establishing the overall environmental impacts from using coal as an energy source in the PCC and UCG-IGCC systems. The impact assessment was based on direct comparison of the following inventory values and indices:

- Resource energy consumption (energy in the materials extracted from the earth, as obtained from combustion.
- Greenhouse gas emissions (GGE) expressed as the equivalent mass emission of carbon dioxide – This included global impacts, though their source and magnitude may be at a local scale. The analysis has used Intergovernmental Panel for Climate Change (IPCC) Greenhouse Warming Potentials for GGE
- Nitrogen oxides, which contribute to photochemical smog and acidification - mostly local impacts.
- Sulfur oxides, which contribute to acidification - a regional impact.
- Suspended particulate matter (SPM), includes all size fractions, PM10 and PM2.5 - a local impact.
- Solid waste to landfill - mostly local impacts.
- Solid waste to tailings, includes material stored or re-emplaced mostly as a single material.

This differs from landfill in that the material can often be regarded as re-emplaced or stored for future use. This applies mostly to coal washery rejects, ore beneficiation plant tailings and fly ash. Tailings contribute mostly to local impacts.

It should be noted that the study has not attempted to aggregate any of the emissions into regional or local effects, such as acidification or photochemical smog potential. Excluded from this list is a number of possible emissions to land, air and water, particularly heavy metals and trace elements.

3.6 Sensitivity Analysis

A sensitivity analysis was conducted to determine the parameters that had the largest effects on the results and to determine the impact of the estimated data as well as variations on data on the conclusion. Variables included in the sensitivity analysis were chosen to reflect system areas that had inherently more unknowns in the data as well as areas in which variations will likely occur during normal operations. Each parameter was changed independently of all others so that the magnitude of its effects on the base case being the PCC system could be assessed. Therefore, no one single sensitivity case reflected the best or the worst case scenario for this system. However, any dependence other variables have on the variable being changed is taken into account. For instance, changing the power plants efficiency, affects the amount of coal required at the plant, which in turn affect the coal mining and transportation requirements. These effects were taken automatically into account in the LCA model.

3.7 Displacement Credits

In the LCA, the production of electricity from the coal leads to the production of other by-products such as particulates, emissions and waste. One key by-product produced during the processes was the production of fly ash. Fly ash has a known use as an additive in the cement manufacturing industry. Hence the environmental burdens for the production of the cement are avoided. This was internalised in the LCA for the PCC process as a displacement credit. Similarly, in the UCG-IGCC process, heavy oil is produced as a by-product extracted from the UCG gases. These by-products displace a similar amount of heavy hydrocarbons obtained from crude oil, giving environmental credits. Hence a displacement credit for the process.

3.8 Summary of Methodology

From Chapter 3, it is possible to establish the procedural aspects of conducting the LCA. Key parameters and variables were unpacked providing a better understanding of the scope, challenges and opportunities encountered in the LCA.

CHAPTER 4: LIFE CYCLE ANALYSIS OF CONVENTIONAL PCC AND UCG-IGCC

In this section, the actual LCA for the PCC and UCG-IGCC processes are discussed. This includes details on the systems operations and specifications. Information is also presented on the LCA considerations, data quality requirements, LCA assumptions and the results and findings of the impact assessment.

4.1 LCA for the Convention PCC System

4.1.1 The System Operation: Conventional Pulverised – Fired Electricity Generation

The scope of the BHP's case study was to calculate the average life cycle environmental impacts for the generation of 1 MW of electricity for the PCC plant. The results were used as the basis for comparison with a UCG-IGCC plant. The study included power station construction, extraction and provision of fuels and consumables, transportation, emissions and waste disposal associated with the generation. Figure 10 below illustrates the main processes for the PCC process considered for this LCA.

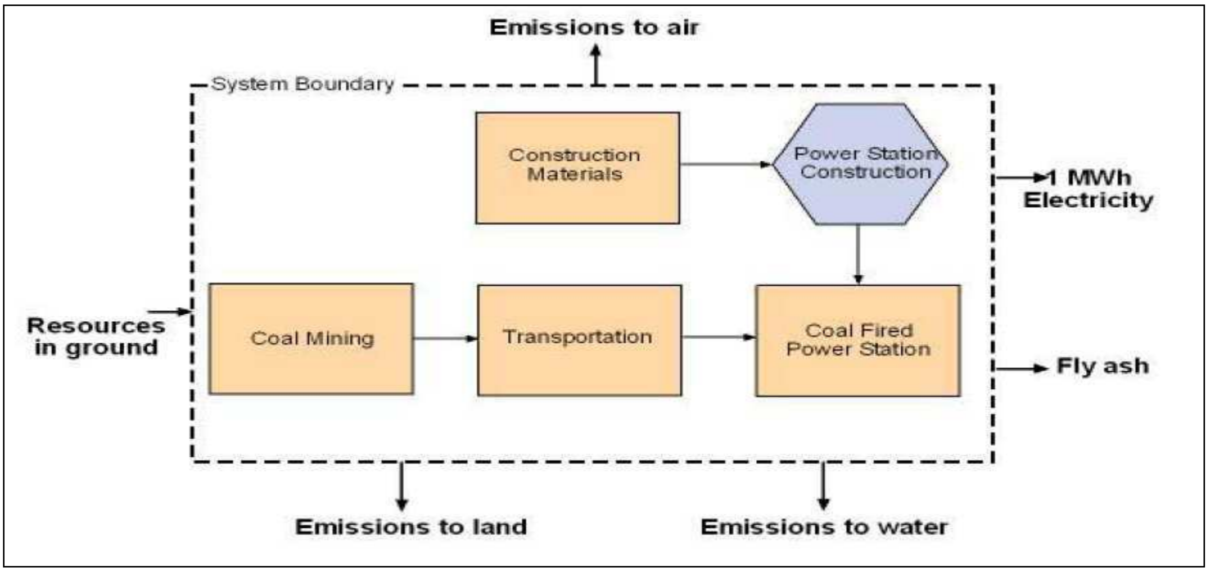


Figure 10: LCA system showing only the main processes for PCC (Source: BHP Billiton, 2002a)

This study was based on a typical base load conventional Coal fired plant connected to the current South African electricity grid.

Table 1. describes the key operating parameter pertaining to the said power station. This data was sourced from a number of references including Eskom reports such as the Eskom Annual Report (2000), National Electricity Regulator Reports (2000), Electricity Supply Statistics for South Africa (2000)

Properties	Values
Total Rated power	*3000MW* *6X500MW*
Water Consumption	*1.75 kL/MWh*
Efficiency	*34.8%*
Capacity factor/Utilization rate	*66%*
Gwh to Grid	*16535Gwh*
Coal Consumption	*8775 Mtpa*
Life Span	*30 Years*

Table 1: Technical Specifications of the PCC plant: (Source:" Electricity Supply Statistics for South Africa 2000", National Electricity Regulator, South Africa, 2000)

4.1.2 The Functional Unit

The functional unit is 1 MW of exported electricity

4.1.3 System Boundaries

The system boundaries for this LCA were drawn as broadly as possible. All of the major processes necessary to produce electricity from coal such as coal mining, equipment manufacturing, transportation, and chemicals production for the mining and power plant operations were included. The material and energy flows of processes involved in the extraction of raw materials and the production of intermediate feedstocks as well as the disposal of wastes were included. However decommissioning and recycling of the power station materials have not been included. A service life of 30 years is assumed.

4.1.4 Construction

The Power Station was built between 1976 and 1979. The first set was commissioned in 1976, with a total station generation capacity of 3000MW. The Power Station was one of the first stations to be supplied with coal from a fully mechanised coal mine, with the coal arriving at the boilers from the mine. The power Station is unique in the sense that each Turbine Generator sets are housed individually and separately from each other. Whereas in Eskom's other Power Stations, all the turbines are housed in a single turbine hall, all placed along the same axis. The station was the first in the Southern Hemisphere to be fitted with the Once – through Boiler (Benson) instead of the usual Drum Boiler (Eskom, 2008). The main materials consumed are shown in Table 2. below. The construction phase included estimates for transportation and earth moving equipment.

Material	**Quantity**
Concrete	*420,000 m³*
Steels – structural, engineering and low alloy	*194,000 t*
Copper – generators and electrical	*2,640 t*
Land requirements for building	*190 ha*
Total site area	*936 ha*

Table 2: Major construction materials: (Source: BHP Billiton, 2002a)

From the above, it is clear that concrete and steel make up the largest quantities required for construction.

4.1.5 Materials and Energy used in Operation

Major resources and other consumables, their source, and mode and distance of transportation are given in Table 3.

Material	***Source***	***Transport***	***Distance (km)***
Coals	*Ingwe, Anglo and other domestic steaming coals*	*Mainly overland conveyor*	*< 10*
Fuel oil, diesel, LPG, petrol	*Sasol*	*Road/rail*	*20-400*
Water	*Usutu water scheme*	*Pumping/pipeline*	*Various systems*
Electricity	*South Africa*	*Distribution grid*	-

Table 3: Major resources and other consumables, their source, and mode and distance of transportation: (Source: BHP Billiton, 2002a)

Fuel

Coal used at the South African power stations is from a range of domestic coal mines. In most cases the power stations are adjacent to coal mines, with conveyor systems transferring the coal from mine to power station (BHP Billiton, 2002). The composition of the coals used in this case study is given in Table 4.

Coal	*C (%)*	*H (%)*	*N (%)*	*S (%)*	*O (%)*	*Moisture (%)*	*Ash (%)*	*Specific energy (GJ/t)*
Kriel Colliery	*51.0*	*2.8*	*1.3*	*0.7*	*9.0*	*4.9*	*30.3*	*19.5*

Table 4: Weighted average composition of coal used (Source: BHP Billiton, 2002a)

Emissions

Electrostatic precipitators were installed as part of the original plant. A sulphur trioxide (SO_3) flue gas conditioning system has since been installed to improve the dust collection efficiency of this plant from approximately 98% to 99,6%, thereby significantly reducing the amount of dust discharged into the atmosphere. Dust suppression is also practised on conveying plants, ash dumps. Fly ash is collected via electrostatic precipitators or bag filters and disposed of in ash dumps or tailings dams.

Greenhouse emissions due to land use change, slow oxidation and spontaneous combustion of stockpiles, waste coal and tailings from mining are not included due to the lack of accurate data. Note, spontaneous combustion of tailings is an issue in some locations. Fugitive methane emissions from underground and open cut coal mines coal in South Africa have been estimated as 2 m^3/t on most run mines have been included in the present analysis. Fugitive dust losses from coal stockpiles were not included due to the lack of reliable data (CIAB, 1994).

Waste Management

Various types of solid waste such as coal ash and domestic waste are generated. All ash is disposed of on an ash dam. Annually the dry sides of the dam are covered with topsoil and revegetated to create useful land, improve the visual quality and suppress wind-blown dust. Domestic waste is disposed of on the registered local municipal waste dump (Eskom, 2008).

Water for Cooling

The plant is operated as a zero liquid effluent discharge site, with all waters used being kept in a closed circuit on site to prevent pollution. Local watercourses are closely monitored to ensure that pollution control measures are effective. The energy required to pump water from the respective catchments to the power stations is included in the analysis (Eskom, 2008).

4.1.6 LCA Considerations

There are no ambiguous technologies or operating issues that significantly affect the LCA results, apart from the utilisation of fly ash for cement. Data is available for the amount of fly ash sold, but there is no breakdown of end-use.

4.1.7 Data Quality Requirements

The estimated data accuracy for key items in the LCA are given in Table 5. together with their impact on the overall LCA values.

	Accuracy	Impact on energy	Impact on GGE
Electricity generation	*±5%*	*±5%*	*±5%*
Coal mining	*±5%*	*< 0.25%*	*< 0.25%*
Coal mining (fugitive methane)	*±25%*	*0%*	*±0.5%*
Transportation	*±5%*	*< 0.5%*	*< 0.5%*

Table 5: Estimated Data Accuracy (Source: BHP Billiton, 2002a)

4.1.8 Allocation Procedures

All environmental impacts (including any displacement credits) are allocated to the functional unit, ie. 1 MWh of exported electricity.

4.1.9 Assumptions

Generation:
Based on the current grid generators in South Africa, which is consists of 89.1% coal fired, 6.6% nuclear, 4.2% hydroelectric with the remainder being small gas turbines (percentages are on power sent out basis). Most of the generating capacity (95%) is owned by Eskom, a government controlled company.

Coal:
Coal for power generation is from 100% domestic supply (Pinheiro, 1999.)

Carbon Dioxide
The generally accepted figure is that 99% of the carbon in the coal is assumed to be converted to carbon dioxide in PCC boiler.

Carbon monoxide, Nitrogen oxides
Australian NGGIC emissions for coal fired and gas turbine power generation are used. (NGGIC, 1996).

Nitrogen dioxides:
Emissions from power stations based on average data reported by Eskom. Emissions from transportation *etc* based on US EPA factors.

Sulphur dioxides:
Based on fuel sulfur composition and 90% conversion to Sulphur dioxides, with the type of sulphur emission control

SPM:
Based on information obtained the Eskom Environment Report for large coal fired stations only (Eskom Environmental Report, 2000).

Methane:
Methane emissions from coal mining are based on estimates from the IEA and World Coal Institute (IEA, 2001).

Fresh water:
Based on information from the Eskom Environment Report - for large coal fired power stations only. Estimates have been made for smaller stations based on overall efficiency and type.

Transport
US EPA emissions and average fuel consumption used.

4.1.10 Impact Assessment

Impact assessment is based on direct comparison of the following inventory values:

- Resource energy
- Fresh water
- GGE (CO_2-e)
- Nitrogen dioxides
- Sulphur dioxides
- SPM
- Solid wastes to landfill (excludes ash remaining in-situ).

4.1.11 Results

In this section, the outcomes of the above mentioned inputs pertaining to the technical operating specifications and the materials and energy used in operation were allocated to the functional unit of 1 MWh for the energy and raw material flows. The major environmental stressors relating to these as seen above were then tabled showing the inputs and outputs pertinent to the PCC process indicated below as impact assessment values. These values were then graphically displayed with and without the displacement credits. A section of the main findings concludes the chapter. As mentioned above in Sections 3.1 and 3.5, the impact assessment values marks the basis of comparison with UCG-IGCC process.

4.1.11.1 Energy and Raw Material Flows

Resources consumed	**Amount**	**Primary use**
Coal - black (Mtpa)	*8775*	*Power generation*
Copper ore (kg)	*0.14*	*Copper wiring, generators*
Dolomite (kg)	*0.07*	*Steel for construction*
Gypsum (kg)	*0.018*	*Cement for construction*
Iron ore (kg)	*0.72*	*Steel for construction*
Limestone (kg)	*0.47*	*Cement and steel for construction*
Magnetite ore (kg)	*0.025*	*Cement and steel for construction*
Manganese ore (kg)	*0.018*	*Steel for construction*
Gas (GJ)	*0.005*	*Utility in construction*
Oil (GJ)	*0.07*	*Utility in construction, transport*
Rock (kg)	*0.936*	*Concrete for construction*
Sand (kg)	*0.936*	*Concrete for construction*
Water (m^3)	*1.75*	*Evaporative cooling water*

Table 6: Resources consumed per MWh of export electricity (Source: BHP Billiton, 2002a)

From Table 6 above, the major consumables for the production of electricity at the said power station are black coal and water. Most of the other consumables are for construction of the power station.

4.1.11.2 Impact Assessment values

A summary of the results for the production of 1 MWh of electricity is shown in Table 7. A discussion on this follows in 4.1.11.4. The impact assessment values are further displayed in the Figure 11 below.

Parameter	**Convention PF**	**Comments**
Inputs		
Resource energy (GJ)	*11.1*	*Total for non-renewable resources*
Energy in tailings	-	*Negligible*
Fresh water (m^3)	*1.75*	*> 98% evaporative cooling water*
Outputs		
GGE (kg CO_2-e)	*970*	*97% from coal combustion*
NO_x (kg)	*3.7*	*99% from coal combustion*
SO_x (kg)	*9.4*	*99.5% from coal combustion*
SPM (g)	*45*	*96% from coal combustion*
Solid waste to tailings (kg)	*171*	*Mostly fly ash*

Table 7: A summary of the results for the production of 1 MWh of electricity (Source: BHP Billiton, 2002a)

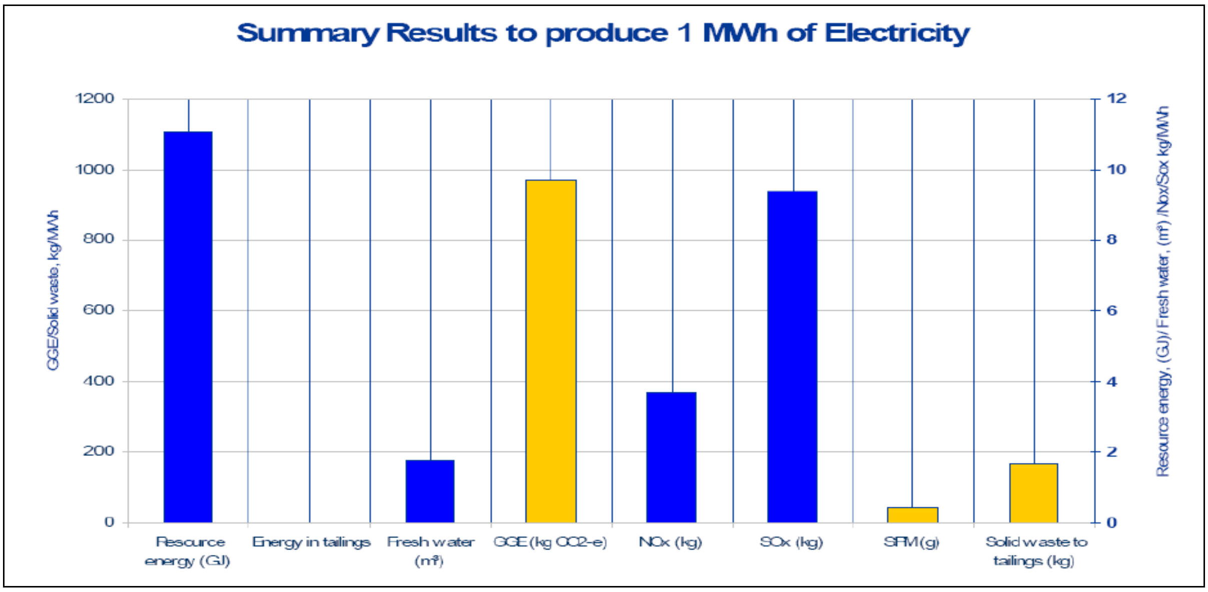


Figure 11: Inputs and outputs for the production of 1 MWh of electricity – PCC

4.1.11.3 System Displacement Credits

As mentioned above in Section 3.7, a potential displacement credit has been calculated assuming that 100% of fly ash produced is used as a cement replacement (see Table 8. below.) In 1999 approximately 1.1 Mt (around 4%) of ash generated at Eskom power stations was sold. Similarly GGE, nitrogen dioxides, sulphur dioxides and SPM emissions are reduced as a knock on effect.

Parameter	**0% Displacement**	**100% Displacement**
Resource energy (GJ)	*11.1*	*10.1*
GGE (kg CO_2-e)	*970*	*873*
NO_x (kg)	*3.7*	*3.4*
SO_x (kg)	*9.4*	*9.3*
SPM (g)	*45*	*42*

Table 8: A summary of the results for the production of 1 MWh of electricity with 100% Displacement (Source: BHP Billiton, 2002a).

Table 8 is graphically displayed in Figure 12.

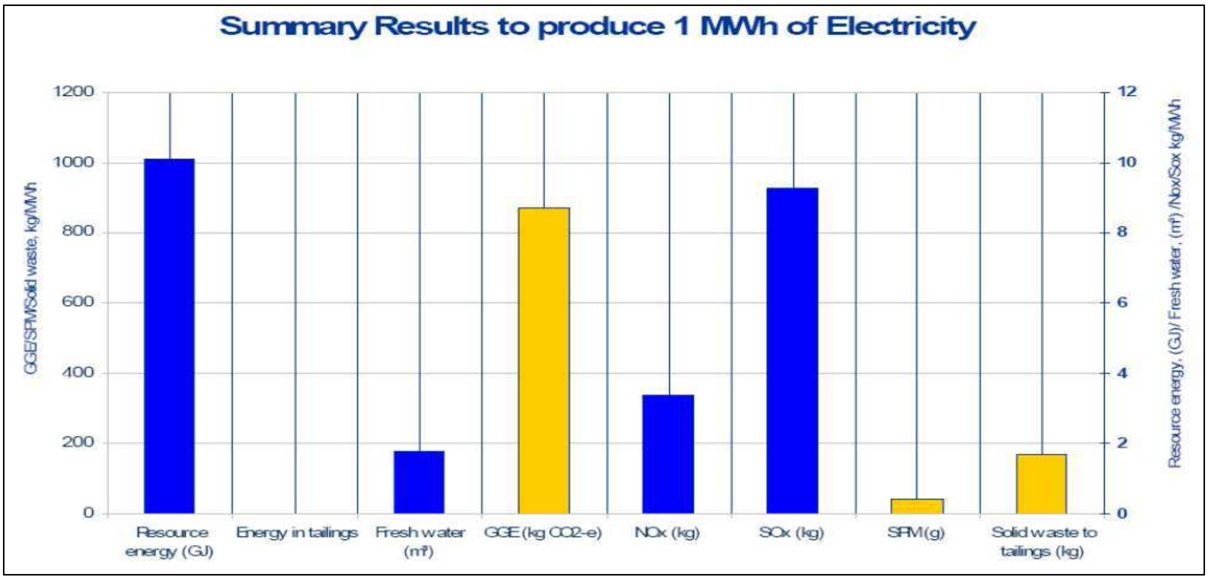


Figure 12: Inputs and outputs for the production of 1 MWh of electricity with 100% Displacements – Conventional PCC

4.1.11.4 Findings

The results show that:

- Over 97% of the resource energy and greenhouse gas emissions associated with electricity generation comes from the combustion of coal at the power station.

- For the conventional cycle, the total GGE is 970 kg carbon dioxide-e/MWh_e (exported). With displacement 873 kg carbon dioxide -e/MWh_e

- Coal mining accounts for approximately 2.5% of the total GGE as a result of fossil fuel consumption of machinery.

- Transport accounts for negligible amounts of resource energy or GGE.

- Sulphur dioxides emissions in this study are slightly higher than those reported by Eskom. This is due primarily to the sulphur content of the coal used in the individual power stations.

- Similarly solid waste in this study is higher than those reported by Eskom. This is due primarily to the ash content of the coals.

4.2 LCA for the UCG-IGCC System

4.2.1 The System Operation: Underground Coal Gasification linked with an Integrated Gasification Combined Cycle (UCG-IGCC)

The scope of this study is to calculate the average life cycle environmental impacts for the generation of 1 MW of electricity from a combined cycle gas turbine firing gas produced from underground (*i.e.* in-situ) gasification of Queensland black coal. It includes key emissions and waste disposal for power station construction, coal gasification, gas extraction, provision of other fuels, consumables and transportation, for the generation of 1 MW of electricity from a combined cycle gas turbine. Figure 13 below illustrates the main processes for UCG with CCGT electricity generation considered for the LCA.

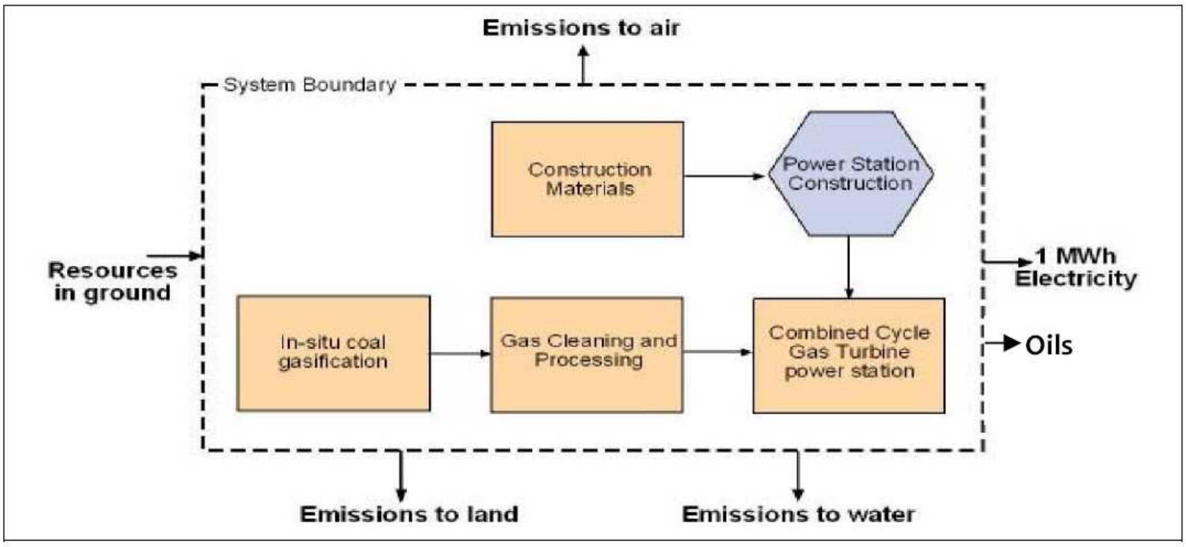


Figure 13: LCA system showing only the main processes for UCG with CCGT electricity generation (Source: BHP Billiton, 2002b)

The LCA was based on the production of electricity from a hypothetical power station assumed to be located near Chinchilla (about 300 km north-west of Brisbane). For the UCG operations, underground gasification data was obtained from the Linc Energy pilot UCG operation, which has produced gas for over 2 years (Walker *et al* 2001). General specifications for this proposed UCG field are given in Table 9.

Property	*Value*
Coal conversion rate	*170.4 t/hour*
Heavy fuel oil by-product	*1.8 t/hour*
Utilisation rate (time on-line)	*92%*
Drilling rate	*35 wells/year*

Table 9: Properties of the UCG operation (Source: BHP Billiton, 2002b)

The process comprised a single turbine, one heat recovery steam generator and one condensing/reheat steam turbine (Walker *et al* 2001) Power plant specifications are given in Table 10 below.

Property	***Value***
Total rated power	*425 MW*
Gas Turbine	*297 MW*
Steam Turbine	*128 MW*
Ancillaries load	*8.6 MW*
UCG electrical requirements	*12.0 MW*
Net power output	*405 MW*
Efficiency (HHV, sent out)	*45.4% @ HHV (53.3% @ LHV)*
UCG gas consumption rate	*25.9 PJ/year*
Utilisation rate (on-line)	*92%*
Service life	*30 years*

Table 10: Properties of the Linc Energy's UCG based IGCC power station (Source: BHP Billiton, 2002b)

4.2.2 The Functional Unit

The functional unit for the UCG-CCGT power station case study is 1 MW of sent out electricity (*ie* after allowance for internal electricity consumption).

4.2.3 System Boundaries

The system boundary for UCG-IGCC setup includes power station construction, UCG and gas processing, power generation, and the provision of other fuels and consumables, all transportation, and waste disposal. A service life of 30 years is assumed and capital materials requirements apportioned per MW over this period. However decommissioning and recycling of the power station materials have not been included.

4.2.4 Construction

The combined cycle turbine gas power station construction was based on data for a 624 MW plant in Spain and scaled down for the 400 MW plant used in this case study. Table 11 below shows the major materials used (BHP Billiton, 2002).

Material	**Quantity**
Concrete	*14,100 m³*
Copper	*310 t*
Steel - cladding	*450 t*
Steel - structural	*4,230 t*

Table 11: Major construction materials for a 400 MW CCGT power station (Source: BHP Billiton, 2002b)

From the above, it is clear that concrete and steel make up the largest quantities required for construction.

4.2.5 Materials and Energy used in Operation

Major material inputs to the power station system, mode of transport and transport distances are given in Table 12.

Material	Source	Transport	Distance (km)
UCG gas	*Chinchilla*	*Pipeline*	*5*
Water	*Condamine River, Chinchilla*	*Pipeline*	*5*
Concrete	*Dalby*	*Road*	*85*
Steel - structure	*Port Kembla-Brisban*	*Sea*	*900*
	Brisbane-Chinchilla	*Road*	*300*
Steel - Cladding	*Port Kembla-Brisban*	*Sea*	*900*
	Brisbane-Chinchilla	*Road*	*300*

Table 12: Major resources and other consumables, their source, and mode and distance of transportation (Source: BHP Billiton, 2002b)

Fuel

Surat basin coals (near Chinchilla) are gasified in-situ to produce the fuel gas. The in-ground composition of the coal is shown in Table 13 and the composition of the product gas is shown in Table 14.

Coal	C (%)	H (%)	N (%)	S (%)	O (%)	Moisture (%)	Ash (%)	Specific energy (GJ/t)
Surat Coal	*49.74*	*3.82*	*0.69*	*0.32*	*8.93*	*12.5*	*24.0*	*20.7*

Table 13: Average composition of Surat Coal (Source: BHP Billiton, 2002b)

Component	***Vol %***
CH_4	*7.0%*
C_2H_6	*0.4%*
C_3H_8	*0.2%*
C_4H_{10}	*0.2%*
CO	*6.0%*
H_2	*18.0%*
CO_2	*16.0%*
N_2	*35.6%*
H_2O	*16.5%*
H_2S	*0.1%*
SO_2	*0.3 ppm*
Specific energy (HHV)	***6.59 MJ/Nm³***

Table 14: Composition of UCG gas to CCGT (after processing) (Source: BHP Billiton, 2002b)

Cooling

The plant is assumed to be cooled using wet cooling with cooling tower makeup water (for condenser cooling) pumped from the bores close to the site. From thermodynamic calculations, an estimated 3.37 Gl of water will be required for the power station each year; however, 0.19 Gl/year of water is produced by the UCG plant and offsets the total amount of makeup water required to 3.18 Gl/year (or 0.97m^3/MWh). Note, no fresh water is required for gas production, as this is provided by underground aquifers by controlling void pressure and gasification rate (an essential part of Linc Energy technology).

Waste management

There are no significant solid wastes generated from UCG-CCGT, as most of the coal ash remains in-situ (underground).

4.2.6 LCA Considerations

Due to the location of the plant it is possible that the plant would be dry cooled and if so, the efficiency stated in Table 10 would be lower. No fresh water is required for gas production, as this is provided by underground aquifers by controlling void pressure and gasification rate (an essential part of Linc Energy technology).

4.2.7 Data Quality Requirements

For UCG –IGCC, the estimated data accuracies for key items in the LCA are given in Table 15 below together with the overall impacts on the LCA values.

	Accuracy	Impact on energy	Impact on GGE
Power station construction	*±30%*	*< 0.3%*	*< 0.3%*
Electricity generation	*±2%*	*±2%*	*±2%*
UCG process	*±5%*	*< 1%*	*< 1%*
Transportation	*±20%*	*< 0.5%*	*< 0.5%*

Table 15: Estimated Data Accuracy (Source: BHP Billiton, 2002b)

4.2.8 Allocation Procedures

All environmental impacts (including any displacement credits) are allocated to the functional unit, *ie* 1 MWh of exported electricity.

4.2.9 Assumptions

Technology

The technology utilized is based on Linc Energy’s proposed 400 MW combined cycle power station located near Chinchilla with a 45.4% net thermal efficiency. UCG technology for the project is provided by Ergo Exergy Inc. (Canada). Linc Energy supplied efficiency and emissions data calculated by Herman Research Laboratories (HRL), an organization which was formerly part of the State Electricty Commission of Victoria.

Coal

Coal is gasified in-situ from wells drilled from the surface. The extracted coal gas is then piped to the adjacent power station.

Coal gas

As stated in the BHP report, coal composition and coal gas production details and compositions were based on data supplied from Linc Energy

Carbon dioxide, Nitrogen dioxides, Sulphur dioxides

Carbon dioxide emissions were calculated from efficiency and gas composition data provided by Linc Energy, and it was assumed that no flaring of excess gas would be required. Nitrogen dioxides and Sulphur dioxides emissions were calculated from specific turbine emissions performance provided by Linc Energy from data provided by the equipment manufacturer and HRL.

Coal bed methane emissions

Assumes that there is no methane leakage from UCG operations, and that all coal bed methane reports to the gas turbine fuel gas. In addition, no production well venting into the atmosphere is required as part of normal UCG operations

Transport

National Greenhouse Gas Inventory Committee (NGGIC) emissions and average fuel consumption are used.

4.2.10 Impact Assessment

Impact assessment is based on direct comparison of the following inventory values with conventional and UCG-IGCC:

- Resource energy
- Fresh water
- GGE (CO_2-e)
- Nitrogen dioxides
- Sulphur dioxides
- SPM
- Solid wastes to landfill (excludes ash remaining in-situ).

4.2.11 Results

4.2.11.1 Energy and Raw Material Flows

A summary of the resources consumed for the production of 1 MWh of electricity from Linc Energy's proposed UCG-CCGT power system is shown in Table 16.

Resources consumed	Value	Primary use
Bauxite (kg)	*0.0014*	*Aluminium (for steel production)*
Coal - black (kg)	*424*	*Coal (both gasified and residual coal)*
Copper ore (kg)	*0.089*	*Copper (wiring, generators)*
Dolomite (kg)	*0.0046*	*Steel (power station construction)*
Gypsum (kg)	*0.0032*	*Cement (power station construction)*
Iron ore (kg)	*0.105*	*Steel (power station construction)*
Limestone (kg)	*0.094*	*Cement, steel (power station construction)*
Magnesite (kg)	*0.0020*	*Steel (power station construction)*
Manganese ore (kg)	*0.0022*	*Steel (power station construction)*
Natural gas (GJ)	*0.00027*	*Manufacturing power station materials*
Oil (GJ)	*0.0017*	*Diesel fuel for well drilling*
Rock (kg)	*0.185*	*Aggregate in concrete (power station construction)*
Sand (kg)	*0.189*	*Aggregate in concrete (power station construction)*
Water (m^3)	*0.89*	*Cooling water make-up*

Table 16: Resources consumed per MWh of electricity exported (Source: BHP Billiton, 2002b)

The major consumables for the overall production system are coal for the UCG process and water for condenser cooling towers. There are numerous other consumables, mostly used in power station construction, and establishment of the gas field. On-going repairs and maintenance, and gas field advancement (piping and concrete sealing plugs for spent wells) are minor contributors.

4.2.11.2 Impact Assessment values

A summary of the results for the production of 1 MWh of electricity is shown in Table 17. A discussion on this follows in Section 4.2.11.4. The impact assessment values are further displayed in the Figure 14 below.

Parameter	***UCG - IGCC***	***Comments***
Inputs		
Resource energy (GJ)	*8.79*	*Non-renewable resource energy, mostly coal*
Fresh water (m^3)	*0.89*	*Evaporative cooling for condensers*
Outputs		
GGE (kg (CO_2-e)	*708*	*Mostly from combustion in power plant*
NO_x (kg)	*1.53*	*Mostly from combustion in power plant*
SO_x (kg)	*3.29*	*Mostly from combustion in power plant*
SPM (g)	*0.10*	*Mostly from construction*
Ash (kg)	*Negligible*	*Retained underground*
Solid waste to tailings (kg)	*0.47*	*Mostly from construction*

Table 17: A summary of the results for the production of 1 MWh of electricity (Source*:* BHP Billiton, 2002b)

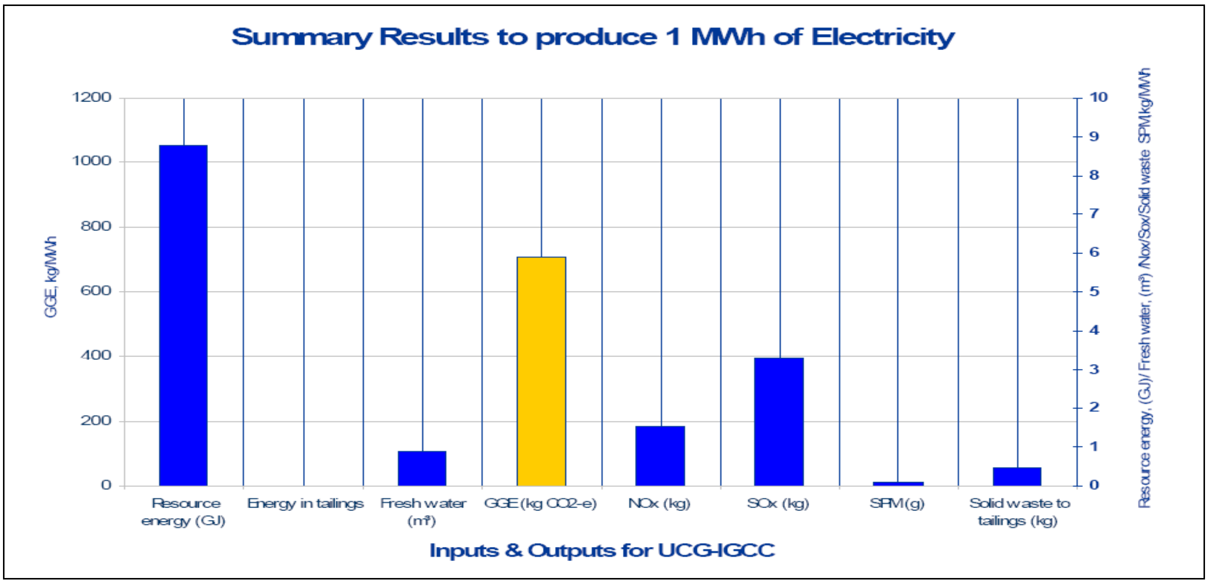


Figure 14: Inputs and outputs for the production of 1 MWh of electricity – UCG-IGCC

4.2.11.3 System Displacement Credits

As mentioned above in Section 3.7 displacement credits can be calculated. Based on pilot plant studies, an estimated 4.45 kg/MWhe (approximately 5 L) of heavy oils will be extracted from the UCG gases. These by-products will displace a similar amount of heavy hydrocarbons obtained from crude oil, giving environmental credits. These credits were taken from LCA values for the production of heavy hydrocarbons from conventional oil wells (including oil refining) and are shown in Table 19.

Parameter	**Value**
Resource energy (GJ)	*48.19*
GGE (kg CO_2-e)	*421*
NO_x (kg)	*0.92*
SO_x (kg)	*0.16*

Table 18: Resource energy and emissions for the production of 1 t of heavy fuel oil (Source*:* BHP Billiton, 2002b)

Parameter	**0% Displacement**	**100% Displacement for by-products**
Resource energy (GJ)	*8.79*	*8.58*
GGE (kg CO_2-e)	*708*	*706*
NO_x (kg)	*1.53*	*1.53*
SO_x (kg)	*3.29*	*3.29*

Table 19: Resource energy and emissions for 1 MWh with/without displacement credits for heavy oil by-products (Source*:* BHP Billiton, 2002b)

Displacement credits for hydrocarbons give a small benefit; resource energy is reduced by around 2% and GGE is reduced by < 0.5%.

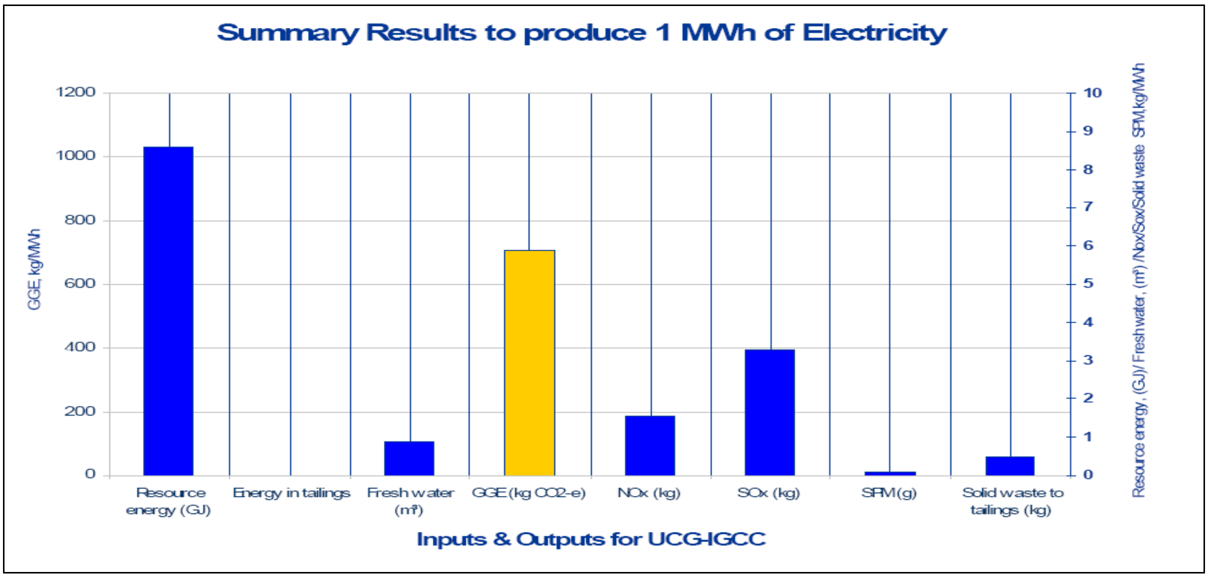


Figure15: Inputs and outputs for the production of 1 MWh of electricity with 100% Displacements – UCG-IGCC

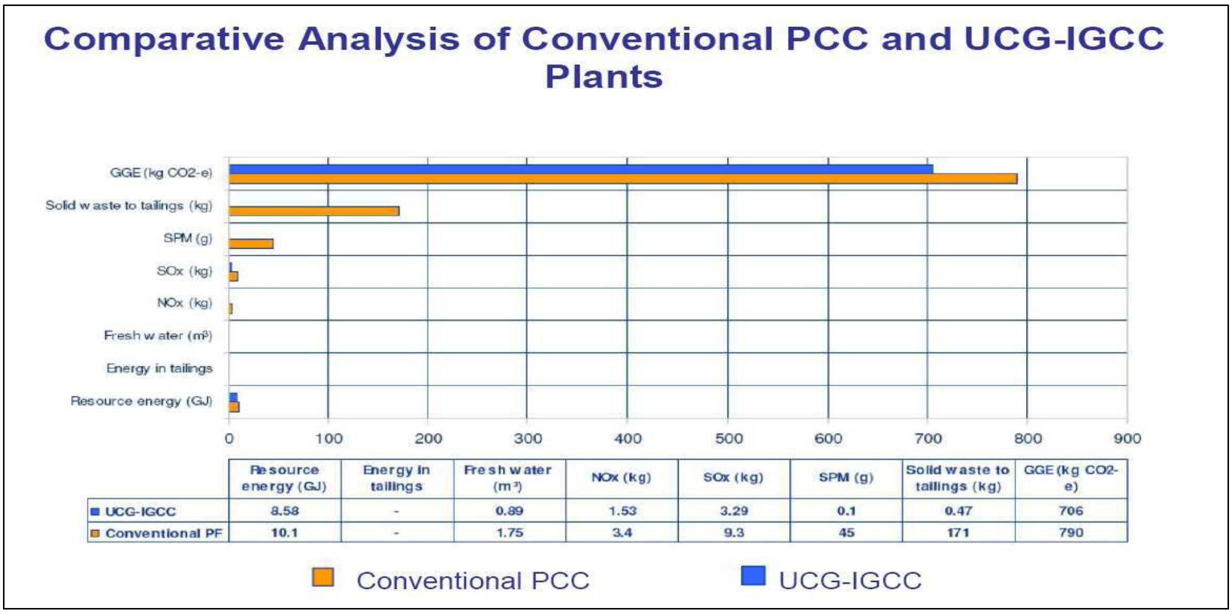
4.2.11.4 Findings

The main findings are that:

- The overall specific GGE is 708 kg carbon dioxide-e/MWh$_e$ (exported). With displacement 706 kg carbon dioxide -e/MWh$_e$
- Resource energy consumption is 8.79 GJ/MWh, which includes the coal seam within the boundaries of the gas field, which is not gasified (*ie* residual coal/other hydrocarbons). With displacement 8.79 GJ/MWh
- 0.19 Gl/year of water is produced by the UCG plant and offsets the total amount of makeup water required to 3.18 GL/year (or 0.97m ^{3}/MWh).

4.3 Comparison and Discussion

After conducting a LCA for both PCC and UCG-IGCC processes, as per objective three in Section 1.3, a comparative analysis on the environmental stressors mentioned in the impact assessment for PCC and UCG-IGCC were conducted. The major findings were then discussed. Figure 16 below illustrates a comparative analysis of the two technologies.



	Resource energy (GJ)	Energy in tailings	Fresh water (m³)	NOx (kg)	SOx (kg)	SPM (g)	Solid waste to tailings (kg)	GGE (kg CO2-e)
■ UCG-IGCC	8.58	-	0.89	1.53	3.29	0.1	0.47	706
■ Conventional PF	10.1	-	1.75	3.4	9.3	45	171	790

Figure 16: Comparative Analysis of Conventional PCC and UCG-IGCC Plants

From Figure16 above, it is clear that there is an overall reduction in the variables measured between the two technologies. The UCG-IGCC technology has proven to be more sustainable than the Conventional PCC technology. Reduction percentages from PCC to UCG-ICGG are as follows:

1. Resource energy **- 15%** reduction
2. Fresh water – **49.1%** reduction
3. GGE (CO_2-e) – **11%** reduction
4. Nitrogen dioxides **- 55%** reduction
5. Sulphur dioxides – **65%** reduction
6. SPM – **99.7%** reduction
7. Solid wastes to landfill – **99.7%** reduction

In terms of total air emissions, GGE are emitted in the greatest quantity, accounting for the bulk of the total air emissions for both systems examined. The majority of the GGE are emitted during coal combustion. Because this amount is so large, it overshadows the GGE from the other process steps within the LCA.

Aside from carbon dioxide, the next highest air emissions include particulates, sulphur dioxides and nitrogen dioxides. Nearly all of the methane comes from the coal mining operations. For the conventional PCC system, the majority of the particulates come from the production of limestone and as a result of the combustion of poor quality associated with South African coals. The UCG-IGCC system shows significant reductions in these emissions which supports the technology as a more sustainable alternative.

An important result of this study is that large amounts of energy are consumed in upstream processes. For the PCC power plant systems, the energy consumed to mine and transport the coal by conveyor accounts for a large proportion of the total non-coal system energy consumption. As the UCG-IGCC system does not require a mining process, it naturally uses less energy in its life cycle. Overall, as expected, the largest amount of energy consumed in each system is the energy contained in the coal fed to the power plant. The coal energy is about 94% of the total system energy for each of the systems.

More water is required for the conventional PCC attributed to the plants design. The UCG-IGCC uses less water and as an added benefit, 0.19 Gl/year of water is produced by the UCG plant and offsets the total amount of used.

With regard to solid wastes to landfill, the UCG-IGCC system proves to be very efficient as most of the coal ash remains in-situ or underground. The PCC system produces large amounts of ash which are disposed of in land fill sites. Assuming that the fly ash is utilised as a raw material in other process streams like cement manufacture, an opportunity for displacement credits exist.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

As stated in Section 1.3, the aims of the research were expressed in four main objectives. They included:

1. conduct LCA for PCC,
2. conduct LCA for UCG linked with an IGCC,
3. a comparative analysis on like aspects between PCC and UCG-IGCC

The first three objectives were met and the outcomes discussed in the relevant sections. In meeting the fourth and final objective this chapter concludes the report with a discussion on the outcome of analytical results and recommendations provided on the deployment of LCA.

The primary goal of this LCA was to assess the environmental aspects of producing electricity from two coal-fired power systems. The focus of this initial work was on an inventory of all resources, environmental emissions, and energy flows of the systems, studied in a cradle-to-gate manner.

This study utilized LCA to explore the environmental impacts of pollutant emissions and energy consumption. The results provide the priorities of fossil fuel for electric power via LCA. Even though LCA studies have a common problem of data sources and choice of the factors for the evaluation method, they can still function as an important reference in situations involving technology alternative evaluation and priority setting. This study attempted to evaluate to competing technologies to yield a definitive result based on the environmental stressors identified. Based on the results, gas fired combined cycle has the best improvement potential.

However, one issue remains regarding the deployment of LCA. There are no legal requirements around the world including South Africa to carry out LCA studies. There is limited reference to LCA in government policies and documentation despite its ability to enable scientifically based decision making to implement Environmental Management Principles.

Further challenges were discussed at a United Nations Environmental Programme Initiative (UNEP, 2003). These challenges are all noted below and included the:

- Absence of a perceived need for LCA

A general lack of environmental awareness and a lack of drivers for chain management and responsibility have created a barrier to development. One of the major impediments for life cycle based policies is the “Stockholm Principles” which state that every country is responsible for its own resources, as long as it causes no harm to any other country. A further complication is the World Trade Organisation agreement that forbids discrimination on the basis of environmental information.

- Scarcity of LCA expertise

It was noted that there is a scarcity of expertise for performing and understanding LCA studies in developing countries. This was further amplified in the comments that communication about LCA methods and study outputs, particularly to policy makers is a problem.

• Cost of LCA Studies

The high level of expert knowledge required by complex LCAs, coupled with the need to purchase data from commercial databases suggest high costs. This is compounded by the added costs of ISO requirements for review.

• Access to High Quality Data

Data quality and availability, particularly for developing countries creates a major practical bottleneck in LCA studies.

• Lack of user-friendly and widely recognised Life Cycle Impact Assessment (LCIA) methods

Methodological barriers in LCIA are related to the lack of generally agreed methods and this appears not to be adequately addressed through ISO standardisation.

• Incorrect perception of the applications of LCA in relation to other tools

There is an incorrect perception of the applicability of LCA and its relationship to other environmental management tools. For example, sophisticated LCIA studies are frequently, incorrectly, compared to environmental risk assessment studies.

Subsequent to the identification of these shortcomings, the United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) have made strides in addressing some of these shortcomings by launching an International Life Cycle Partnership, known as the Life Cycle Initiative, to enable users around the world to put life cycle thinking into effective practice.

The Initiative responds the call by Governments around the world for a Life Cycle economy in the Malmo Declaration (2000). It contributes to the 10-Year Framework of Programmes to promote sustainable consumption and production patterns, as requested at the World Summit on Sustainable Development in Johannesburg (2002) (UNEP, 2010).

According to the UNEP (2010), added value of the Initiative includes:

- The ability to access and mobilize an established and growing global network of over 2000 interested members who have been and continue to be interested in understanding and advancing Life Cycle approaches worldwide. These experts represent industry, Government, academics and the service sectors and are the leaders in developing and applying Life Cycle Assessment (LCA) and Life Cycle Management (LCM) worldwide.
- The ability to gather and manage examples of best practices and Life Cycle achievements across the world
- The status of being considered as one stop shop for Life Cycle approaches.
- The opportunity to connect science and decision making in policy and business with the supply and demand side of Life Cycle approaches. Therefore, and opportunity exists to become the global authority for consensus building and peer review on methodological questions and environmental assessments of natural resources, materials and products in the field of science.

The partnership has completed phase 1. Phase 2 will build on the Life Cycle Initiative’s continual strength to maintain and enhance life cycle assessment and management methodologies and build capacity globally. As we look to the future, LCA and LCM knowledge is the Life Cycle Initiative’s anchor, but we will advance activities on LCA and LCM to make a difference within the real world.

The objectives for Phase 2 are the following ones:

Objective 1: Enhance the global consensus and relevance of existing and emerging life cycle approaches methodology;

Objective 2: Facilitate the use of life cycle approaches worldwide by encouraging life cycle thinking in decision-making in business, government and the general public about natural resources, materials and products targeted at consumption clusters;

Objective 3: Expanding capability worldwide to apply and to improve life cycle approaches.

The recommendations in this regard are that LCA must contribute substantially to the quality of integrated decision making, particularly against the context of a government's commitments to sustainable development. As an additional tool in the environmental management toolbox, it must assist in raising awareness on integrated environmental management and sustainability issues and must encourage a greater degree of inter-disciplinary linkages.

There is room for greater use of LCA. Current usage is limited but significant growth in this area will depend upon extensive capacity building in both academic and technical fields through initives spearheaded by organisations such as the UNEP. Co-operative projects such as the LCA Initiative must assist in not only developing the skills and expertise but also by bridging the gap in terms of databases, development of localised categories and harmonisation of methodologies that cut across all international divides.

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