Site Characterization, Sustainability Evaluation and Life Cycle Emissions Assessment of Underground Coal Gasification

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Dissertation submitted to the Faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Mining Engineering

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September 6, 2012
Blacksburg, Virginia

Keywords: Underground Coal Gasification, Site Characteristics, Sustainability and Sustainable Development, GIS, Life Cycle Assessment, Greenhouse Gas Emissions

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Abstract

Underground Coal Gasification (UCG), although not a new concept, is now attracting considerable global attention as a viable process to provide a “clean” and economic fuel from coal. Climate change legislation and the declining position of coal reserves (i.e., deeper and thinner seams) in many parts of the world are promoting and fueling the UCG renaissance.

This research presents an analysis of operational parameters of UCG technology to determine their significance and to evaluate the effective range of values for proper control of the process. The study indicates that cavity pressures, gas and water flow rates, development of linkage between wells, and continuous monitoring are the most important operating parameters.

A protocol for the selection of suitable sites for UCG projects is presented in this study. The site selection criteria are developed based on successes and failures of previous experiments and pilot studies. The criteria take into account the site characteristics, coal quality parameters, hydrology of the area, availability of infrastructure and regulatory and environmental restrictions on sites. These criteria highlight the merits and demerits of the selected parameters, their importance in site selection and their economic and environmental potentials.

Based on the site selection criteria, a GIS model is developed to assist in selecting suitable sites for gasification in any given area of interest. This GIS model can be used as a decision support tool as well since it helps in establishing the tradeoff levels between factors, ranking and scaling of factors, and, most importantly, evaluating inherent risks associated with each decision set.

The potential of UCG to conform to different frameworks defined to assess the capability and potential of any project that merits the label, “sustainable,” has been evaluated. It has been established that UCG can integrate economic activity with ecosystem integrity, respect for the rights of future generations to the use of resources and the attainment of sustainable and equitable social and economic benefits. The important aspects of UCG that need to be considered for its sustainable development are highlighted.

In addition, the environmental benefits of UCG have been evaluated in terms of its potential for reduction in greenhouse gas (GHG) emissions. The findings indicate that UCG significantly reduces GHG emissions compared to other competitive coal exploiting technologies. A model to compute the life cycle greenhouse emissions of UCG has been developed, and it reveals that UCG has distinctive advantages in terms of GHG emissions over other technologies and competes favorably with the latest power generation technologies. In addition to GHG emissions, the environmental impacts of these technologies based on various impact assessment indicators are assessed to determine the position of UCG in the technology mix. It is clear from the analysis that UCG has prominent environmental advantages and has the potential to develop and utilize coal resources in an environmentally friendly and economically sound manner.

Dedication

To my Parents and to my Wife, their love, support
and faith in me is the biggest asset of my life.

Acknowledgements

I thank the God Almighty, the most Beneficent, and the most Merciful. He is the one who has the absolute knowledge and disseminates knowledge among the people as He wills. He has been my Guide in the past and will be in the future.

When I look back to the four years spent in the U.S., I see many wonderful people who helped me transition into Virginia Tech. First and the foremost, my sincere thanks to Dr. Karmis who is one of the nicest persons I have ever met. He is very kind, welcoming, and helpful and I always saw him with these traits throughout my studies. He helped me in my course selections, guided in my research and was very considerate in correcting me whenever I made mistakes. I consider myself very fortunate to be under his guidance in my research endeavors.

I would also like to thank my committee members Dr. Westman, Dr. Karfakis, Dr. Luttrell, Dr. Kray and Dr. Zach. They all are great people and renowned researchers and scientists in their fields. I learned a lot from all of them and their comments and suggestions assisted me in shaping my research.

I am thankful to Nino Ripepi, for his valuable edits, remarks and help in the formatting of various chapters of this dissertation. He also helped me in obtaining the LCA software, SimaPro, and for that, I am obliged to him. I am also grateful to Steve Schafrik, who was always helpful whenever I approached him, which happened a lot during the course of my studies and research. Whenever I had any problem with the software, programming or general course work he was the person I always approached first for help. I learned several good traits from him and enjoyed playing darts with him too.

I would also like to thank Margaret, Brad and Jackie for their help and support. They are the wonderful colleagues and I consider myself lucky to have such helping people during my stay at VT.

My deepest thanks go to my parents, my lovely wife, my wonderful brother, loving sisters and my beautiful kids. Their love and prayers are source of my strength and joy of my life. Finally, I would also like to thank all the people who helped me, my wife and kids feel Blacksburg as a home and treated us like a family.

In the end, I thank Allah Almighty again for His countless blessings and bringing such nice people in my life. I pray to Him, for the good of the knowledge gained and to grant me strength and wisdom to use my abilities in a way that is beneficial to the society.

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List of Abbreviations

AHP: Analytical Hierarchy Process
Bcf: Billion Cubic Feet
BEES: Building for Environmental and Economic Sustainability
CBM: Coalbed Methane
CCS: Carbon Capture and Sequestration
CO_2e: Carbon Dioxide Equivalent
CRIP: Controlled Retraction Injection Point
CTA: Center of Transport Administration, USA
CTL: Coal to Liquid
DoE: Department of Energy, USA
DoS: Department of State, USA
DOT: Department of Transport, USA
DRB: Demonstrated Reserve Base
EIA: Energy Information Administration, USA
EPA: Environmental Protection Agency, USA
EPS: Environmental Priority Strategies
GHG: Greenhouse Gas
GIS: Geographic Information Systems
Gt: Giga Ton=10^9 ton
GTL: Gas to Liquid
GWP: Global Warming Potential
IEA: International Energy Agency
IGCC: Integrated Gasification Combined Cycle
IISD: International Institute for Sustainable Development
IPCC: Intergovernmental Panel on Climate Change
IPCC: Intergovernmental Panel on Climate Change
kcal: Kilo Calorie

kg: Kilogram = 1000 gram

KWh: Kilowatt Hour

LCA: Life Cycle Assessment

LCA: Life Cycle Assessment

MJ: Mega Joules

MMBTU: Million British Thermal Units

MMSD: Mining, Minerals and Sustainable Development

MWh: Megawatt Hour

NETL: National Energy Technology Laboratory, USA

Nm^3: Normal Cubic Meter

OECD: Organization for Economic Co-operation and Development

OWA: Ordered Weighted Average

PCC: Pulverized Coal Combustion

Scfm: Standard Cubic Feet per Minute

SCPC: Supercritical Pulverized Coal Combustion

SNG: Synthetic/Substitute Natural Gas

Tg: Tera gram = 1012 gram= Million Metric tons

TNS: The Natural Step

TRACI: The Reduction and Assessment of Chemical and Other Environmental Impacts

U.S.: United States of America

UCG: Underground Coal Gasification

WLC: Weighted Linear Combination

Chapter 1 - Introduction

1.1 Introduction

Underground or insitu coal gasification (UCG) is a process involving insitu burning and conversion of coal into gaseous product, commonly known as synthetic gas or syngas. This syngas is at high temperature and pressure and can be used for several processes including but not limited to electricity, heat and power generation, feedstock for several chemical processes such as Fischer-Tropsch, synthetic natural gas & hydrogen production, iron reduction and chemical products like ethylene, polyolefin, methanol, petrol, acetic acid and formaldehyde [Liu, Mallet et al. 2003; Courtney 2009; Oukaci 2009]. In its simplest form, the process involves an injection and a production well, drilled up to the coal seam. Then steam, air or oxygen is injected under pressure through the injection well to start combustion process and product gases at high temperature and pressure are collected at the production well.

The composition of syngas is largely H_2, CH_4, CO and CO_2, with a calorific value of 850 -1200 kcal/Nm^3 (~ 3.5 – 5 MJ/m^3) [Ghose and Paul 2007]. However, the composition and calorific value of syngas varies according to the site characteristics (coal ranks, strata type, depth and amount of moisture etc.) and type of gases used for injection (air, oxygen or steam). The calorific value for air injected syngas typically ranges from 4.0-5.5 MJ/m^3 and approximately doubles when oxygen is injected instead of air [Walker 1999].

1.2 Problem Statement

Underground or Insitu Coal Gasification (UCG or UICG), though not a new concept, is now attracting considerable global attention as a viable process to provide a "clean" and economic fuel from coal. This technology has the potential to exploit energy from low grade, deep seated, thin coal seams in an economic, environment friendly and sustainable manner. This technology can be applied to abandoned coal mines, remnants of already exploited reserves and deposits considered uneconomic and technically difficult for conventional mining methods. Despite these economic, environmental and technical benefits, this technology has the potential to create hazards of atmospheric emissions, ground water contamination, uncontrollable cavity growth & underground fires, subsidence, CO_2 management and human impacts like noise, dust, and increased traffic, if the process is not properly managed. Thus, in order to manipulate the full economic and environmental potential of this technology, it is imperative that its development is in line with sustainable development principles, based on proper site selection criteria and environmental impact assessments. As this is a developing technology, many research gaps need to be filled. Some of the most prominent aspects dealt in this research include development of site selection criteria, GIS modeling of selected sites, Life cycle assessment to compare environmental impacts with other competitive technologies and sustainability assessment of UCG.

1.3 Research Objectives

Since UCG is a technology that is currently in development stage, many aspects require focused research to develop it into a mature and commercially acceptable alternate for exploitation of energy from coal. The focus of this research is on the following core objectives:

1. Operational Parameters of UCG
    a. Review of important operational parameters
    b. Analysis of developments in operational criteria
2. Development of site selection criteria
    a. Outline important site selection parameters for UCG
    b. Evaluate the importance of defined parameters for site selection and resource assessment
    c. Application of this criteria to identify potential UCG sites
    d. Development of GIS Model based on defined parameters/criteria
3. Sustainability assessment of UCG operations
    a. Assessment of UCG within sustainable development frameworks
    b. Identify important principles essential for sustainable development of UCG

4. Greenhouse gas reduction potential of UCG
    a. Assessment of key parameters for GHG reduction potential
    b. Theoretical evaluation of key factors
5. Life cycle Assessment of UCG
    a. Life cycle modeling to quantify GHG emissions of UCG
    b. Comparison of UCG and other competitive technologies in terms of GHG emissions
    c. Characterization and impact assessment of UCG and competitive technologies based on various environmental assessment indicators.

1.4 Research Approach

Research approach comprised following steps:

- Literature Review
- Data Collection
- Evaluation of Data
- Modeling
    - Based on available data
    - Based on surrogate data
    - Comparison of models
- Modeling tools/software
    - GIS Modeling
        - ARC GIS
        - IDRISI Taiga
        - MS Access Database
        - Shape Files
        - Raster Images
        - Decision Support Tools
    - LCA Modeling
        - SimaPro 7.3.3
        - Excel worksheets for calculations
- Assessment of Current developments

- Site survey/visits
- Evaluation of developed models
- Rectification of models
- Publication of results
- Dissertation

1.5 Publications

In the course of research for dissertation, following papers either are published or are in the process of publication.

1.5.1 Published Papers

1.5.1.1 Hyder, Z., Karmis, M., ASSESSING THE CONTRIBUTION OF UNDERGROUND IN-SITU COAL GASIFICATION (UICG) WITHIN A SUSTAINABLE DEVELOPMENT FRAMEWORK, Aachen International Mining Symposia, 5th International Conference, "Sustainable Development in the Minerals Industry, SDIMI 2011" June 14-17, 2011 Aachen Germany, Pages 569-579

1.5.1.2 Hyder, Z., Ripepi, N., Karmis, M., Roth, B., UNDERGROUND COAL GASIFICATION IN THE CENTRAL APPALACHIAN REGION, USA: RESOURCE ASSESSMENT, 22nd World Mining Congress and Expo, September 11-16, 2011 Istanbul Turkey

1.5.1.3 Hyder, Z., Ripepi, N., Karmis, M., UNDERGROUND COAL GASIFICATION AND POTENTIAL FOR GREENHOUSE GAS EMISSIONS REDUCTION, CMTC 151155-MS, 2012 Carbon Management Technology Conference, February 7–9 2012, Orlando, Florida, USA DOI: 10.7122/151155-MS, ISBN: 978-1-61399-179-4.

1.5.2 Paper Abstracts Accepted for Publication

1.5.2.1 Hyder, Z., Ripepi, N., Karmis, M., OPERATIONAL AND ENVIRONMENTAL CHARACTERIZATION OF UNDERGROUND COAL GASIFICATION, Symposium on Environmental Considerations in Energy Production, April 14-18, 2013 Charleston, West Virginia

1.5.2.2 Hyder, Z., Ripepi, N., Karmis, M., A GIS MODEL FOR SELECTION OF SUITABLE SITES FOR UNDERGROUND COAL GASIFICATION, 2013 SME Annual Meeting & Exhibit and CMA 115th National Western Mining Conference "Mining: It's About The People", February 24-27, 2013 Denver, Colorado

1.5.3 Papers in the Submission Process

A paper based on “Comparing Life cycle Greenhouse Emissions from Coal and UCG Power Generation” is in process for journal submission.

Chapter 2 - Literature Review

2.1 History of UCG

Underground coal gasification (UCG) is not a new concept and can be traced back to as early as 1868, when Sir William Siemens, a German scientist first presented the idea of burning ash-rich coal underground before the Fellows of the Chemical Society of London [Olness and Gregg 1977]. The famous Russian scientist, Dmitry Mendeleyev mentioned the same idea some twenty years later in 1888, when he remarked that in the future coal would be burned underground and supplied as gas via pipes for consumption. Mendeleyev exclusively suggested his depiction of UCG during a visit to Kizel plant in Ural Russia in 1899, where he gave the idea about controlling the underground coal fires by drilling of injection and production well, with supply of limited air quantity through one pipe and syngas withdrawing by suction though other pipe [Klimenko 2009]. In 1909, Great Britain issued first patent for UCG to an American, A.G. Betts, who presented two different methods of gasifying seams too thin or to poor for mining [Olness and Gregg 1977]. Around 1910, UCG was included in the proposals suggested by a special committee of Britain's leading scientists investigating national energy sources. An English chemist, Sir William Ramsey, who was also serving on the committee, took great interest in the idea of UCG and expanded Bett‘s idea. In 1912, he presented his idea and its merits at the International Smoke Abatement Exhibition, London. His method involved a borehole in the coal and passing of air and steam through the hole to initiate water gas reaction. This first trial experiment got funding but never occurred because of Ramsey's death and the outbreak of World War I[Olness and Gregg 1977] .

For the next several years, no further progress was reported in underground gasification. However, the idea of gasifying coal underground and Ramsey's reports attracted Lenin, who was living in exile in Zurich at that time. Lenin liked the idea of UCG as it had potential of reducing labor requirements and improved working conditions for miners, freeing them from hard underground labor. This reduction of labor could contribute to his idea of shortening the working day to 7 hours or less, a major concern of socialist society. On May 4 1913, Lenin published an article in Pravda highlighting the potential of UCG [Olness and Gregg 1977]. This brought the UCG concept into the political lime light and placed it in the public. Based on the same potentials envisaged by Lenin, Joseph Stalin championed the UCG program in Former Soviet Union. First trials started in about 1928 and for the next five or so decades, Soviets ruled in UCG technology, with total Soviet efforts far exceeding the combined efforts of other nations and commercial UCG plant still working in Angren, Uzbekistan [Brown 2012].

The energy shortage between 1944 and 1959 promoted interest for UCG in Western European coal mining countries and Czechoslovakia, France, Italy and Poland conducted UCG tests. In Britain, experimental work started in 1949 at Newman Spinney in Derbyshire and in Bayton Worcestershire the following year [Thompson, Mann et al. 1976]. However, the work on UCG stopped in the 1960s due to abundance of energy and lower oil prices. European work started again in the 1980s and several UCG tests were carried out in Western Europe [Couch 2009]. The tests were carried out in Belgium in 1982 and in France during 1983 and 1984. In 1989, the European Working Group recommended a series of trials to determine commercial feasibility of UCG in thinner and deeper coal seams of Europe. The first of such trials was undertaken in 1992-1999 by Spain, UK and Belgium with the support of European Commission and was known as “the Spanish trial”. For this trial two fields were proposed, one having coal at a depth of about 600 m to represent southern Europe coal fields and the second at 900 m in bituminous coal typical of mid and northern European fields [Creedy, Garner et al. 2001]. This project demonstrated key technological and research requirements for further development of this technology and highlighted likely environmental impacts.

In the U.S., research and development about UCG started in the 1940s. The program accelerated in the 1970s due to energy crisis and more than 30 experiments were conducted between 1972 and 1989 [PWC. 2008]. The U.S. Department of Energy funded most of these trials [Klimenko 2009]. Most notable of these trials were Hoe Creek, Wyoming and Centralia, Washington. These tests were well documented and provided the basic information for several pilots and commercial tests in other countries. However, groundwater contamination resulting from these pilots and reduced natural gas and oil prices in the 1990s hampered further development and commercialization of UCG projects in the U.S. [PWC. 2008].

2.2 UCG Process Evolution

In its simplest form the UCG, process requires two boreholes, one acting as an injection well and the other as a production well. The linkages between these two wells depend upon the permeability of the coal matrix. The air, steam or oxygen is injected from the injection well under pressure and burning process starts forming the burn cavity. The product gases are collected at the production well for cleaning and other uses. Figure 2.1 depicts the basic concept in the simplest form.

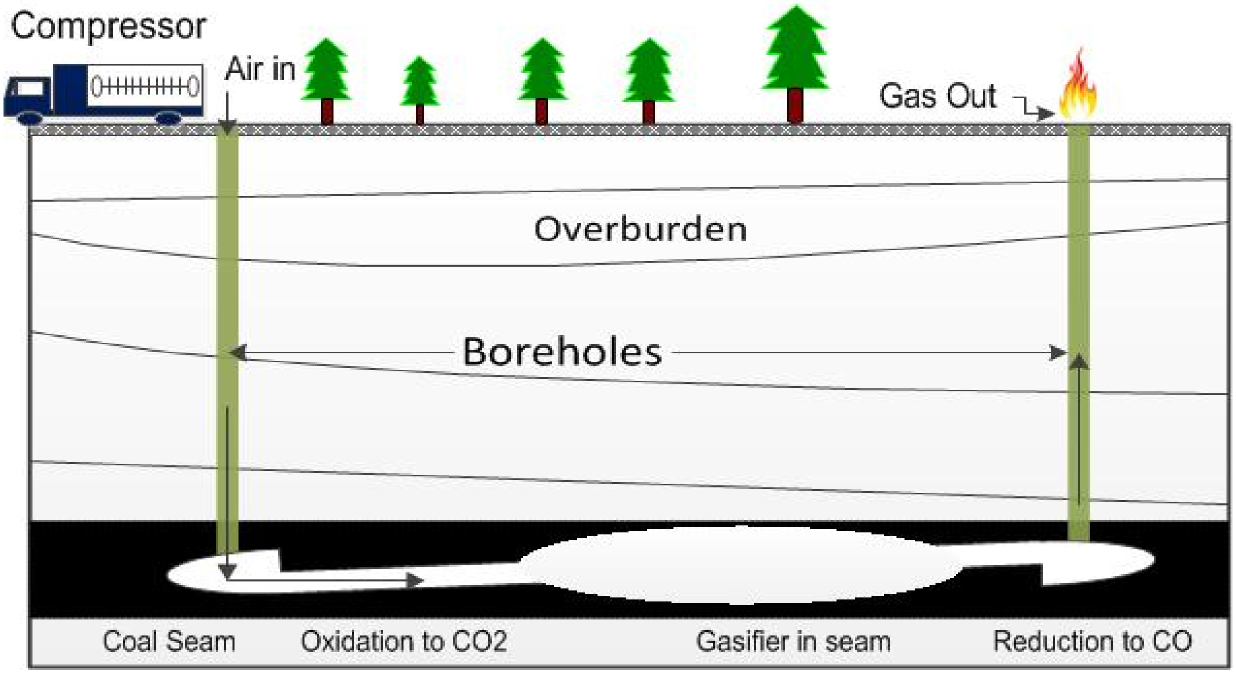


Figure 2.1: Basic concept of UCG

A.G Betts, an American was the first one to get a patent for UCG. Figure 2.2 is the reproduction of the Betts's idea and his patent specifications [Olness and Gregg 1977].

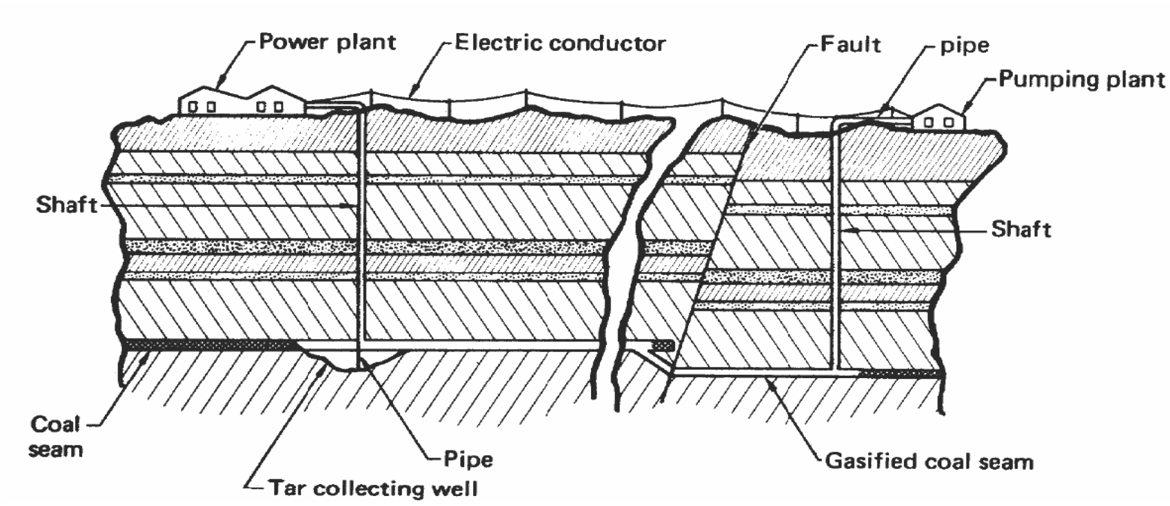


Figure 2.2: Betts's UCG patent

Based on Betts idea, the work on UCG started about a century ago. Several modifications and developments occurred in the course of time, but the basic idea remained the same. Figure 2.3 shows the modern concept of UCG including gas cleaning, CO_2 removal and power generation plants on site.

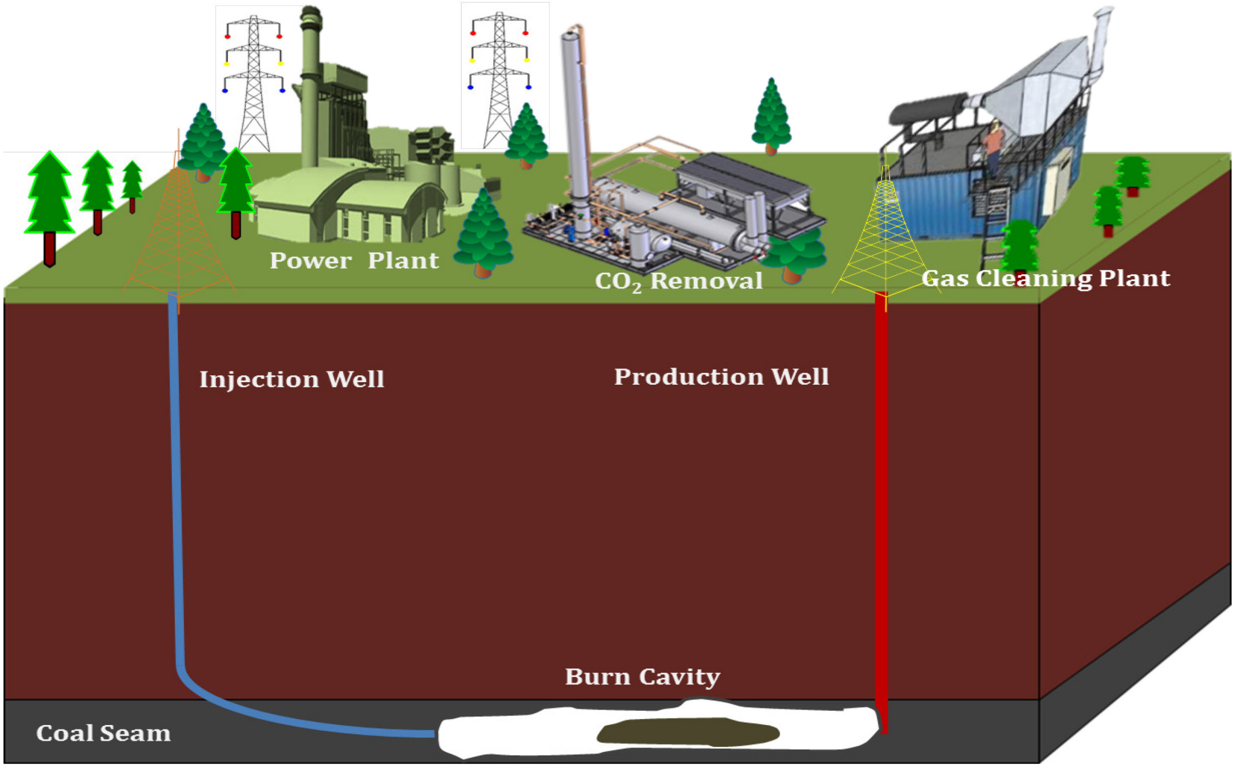


Figure 2.3: Modern UCG concept

2.3 Historical Developments

In early 1930s, the Russians started an extensive research program about UCG. During the next 50 years, they conducted several pilot and commercial trials on UCG. In earlier trials they tried to burn the coal adjacent to the road ways and drifts, however, this process did not prove successful as it burned the produced gas and allowed the air to bypass the burning zone, so they tried boreholes instead of roadways, initially with the holes drilled from the roadways but later on from the surface [Olness and Gregg 1977]. At Lisichansk, the deviated holes were drilled, which was an impressive achievement at that time [Klimenko 2009]. The Russians also developed a method to gasify steeply dipping coal seams, with the borehole drilled from the surface, as shown in Figure 2.4. A steeply sloping seam at Yushno Arbinsk, USSR was developed for UCG, drilling boreholes from the surface [Thompson, Mann et al. 1976].

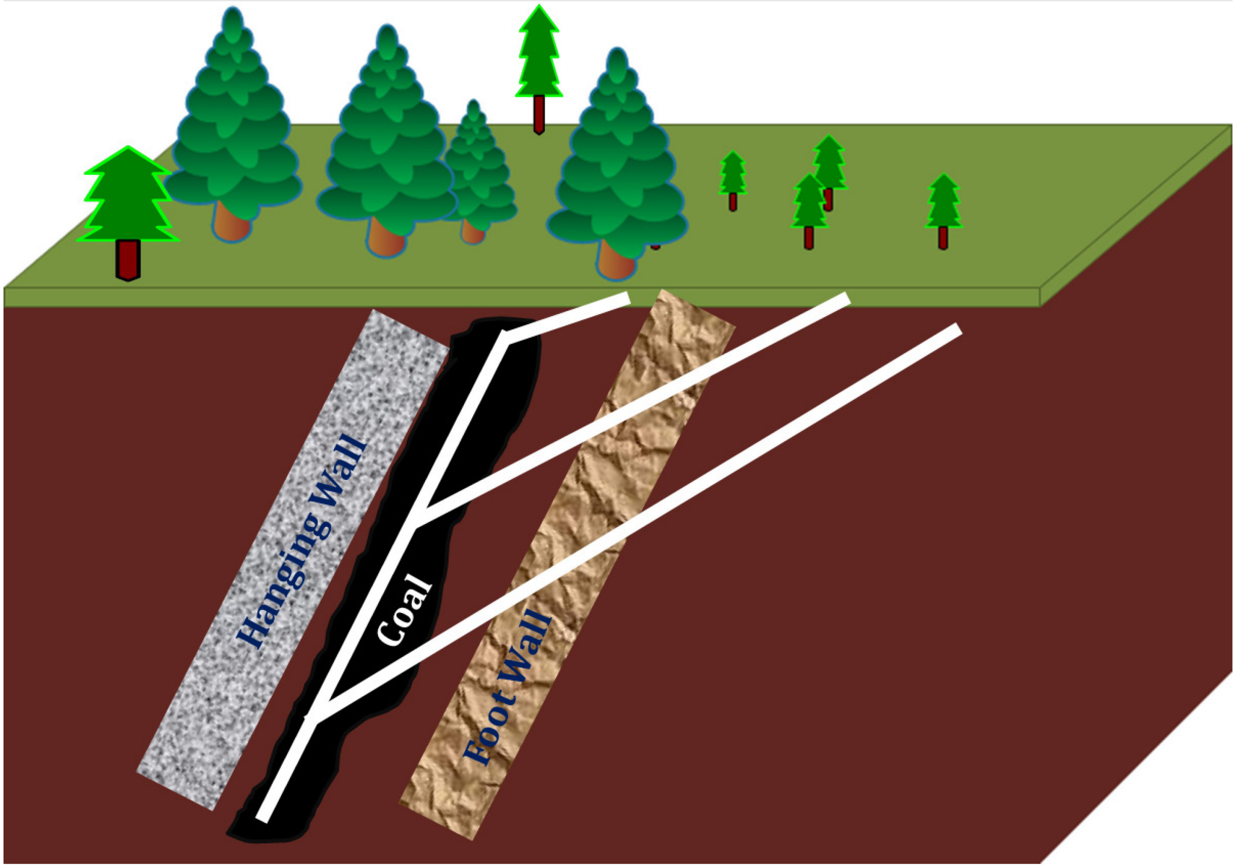


Figure 2.4: Drilling into a steeply inclined seam from the surface

The first trial at Britain started in 1949 at Newman Spinney, adjacent to an opencast site and the seam was developed for UCG by drilling a hole from the exposed surface, initially keeping the hole above the seam and then allowing it to cross through the seam. In another trial at Bayton England, the pneumatic linkage method was tried successfully, with high-pressure air used to promote the linkage and enlarge the cavity between boreholes. In 1958, the National Coal Board England, planned a trial to develop the site at Newman Spinney using the blind borehole technique, where holes were drilled from a roadway or tunnel into the seam and terminated at blind or dead end [Thompson, Mann et al. 1976]. Figure 2.5 is a schematic of this technique.

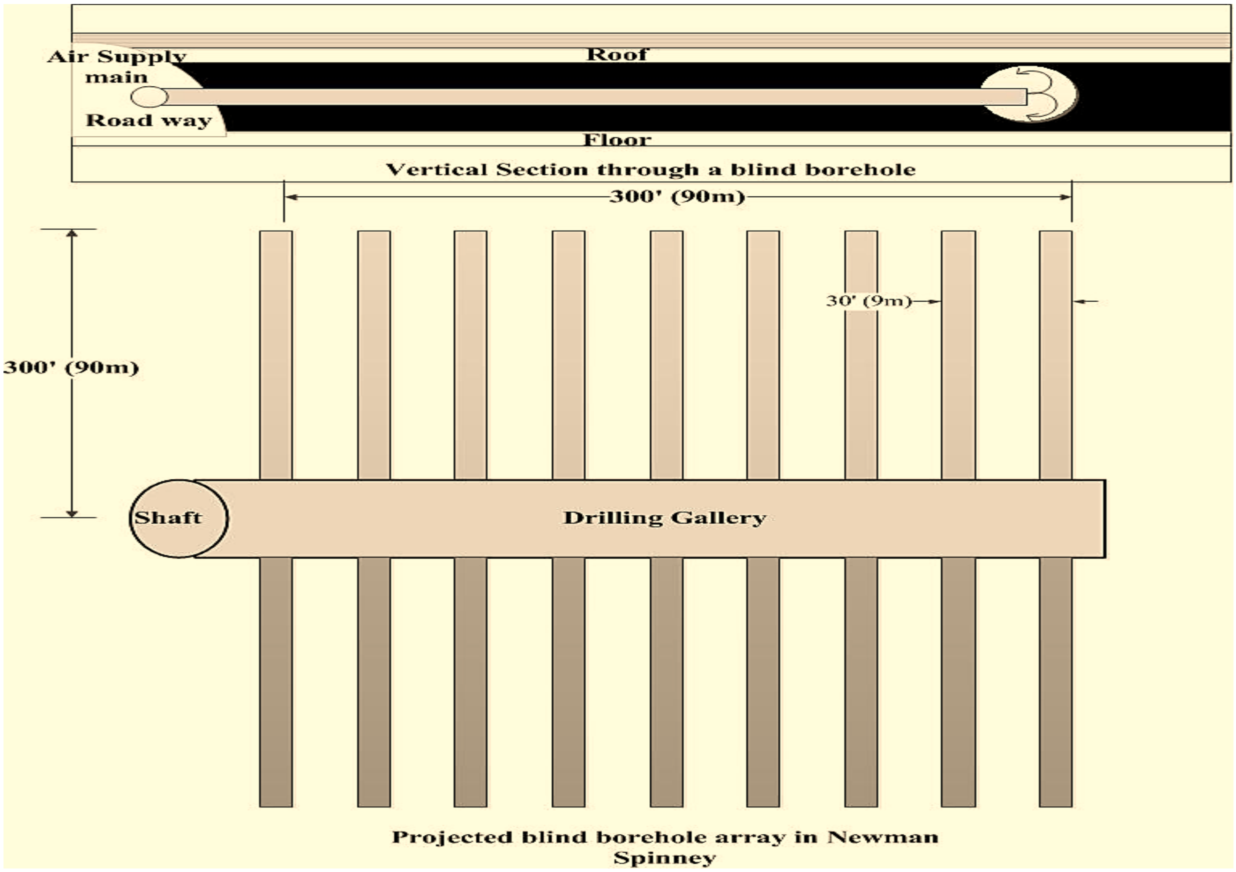


Figure 2.5: Blind borehole method, Newman Spinney

At Newman Spinney another approach to gasifier design was tried based on Russian, Polish and Belgian work at that time in which the entire length of the gallery was ignited by means of wooden sleepers and a broad reaction front advanced until the final form of voids was achieved. From 1962-1966, the working site was exposed by opencast mining and provided a visual look of the site which confirmed the shape and size of the cavities to a remarkable degree [Thompson, Mann et al. 1976], as shown in Figure 2.6.

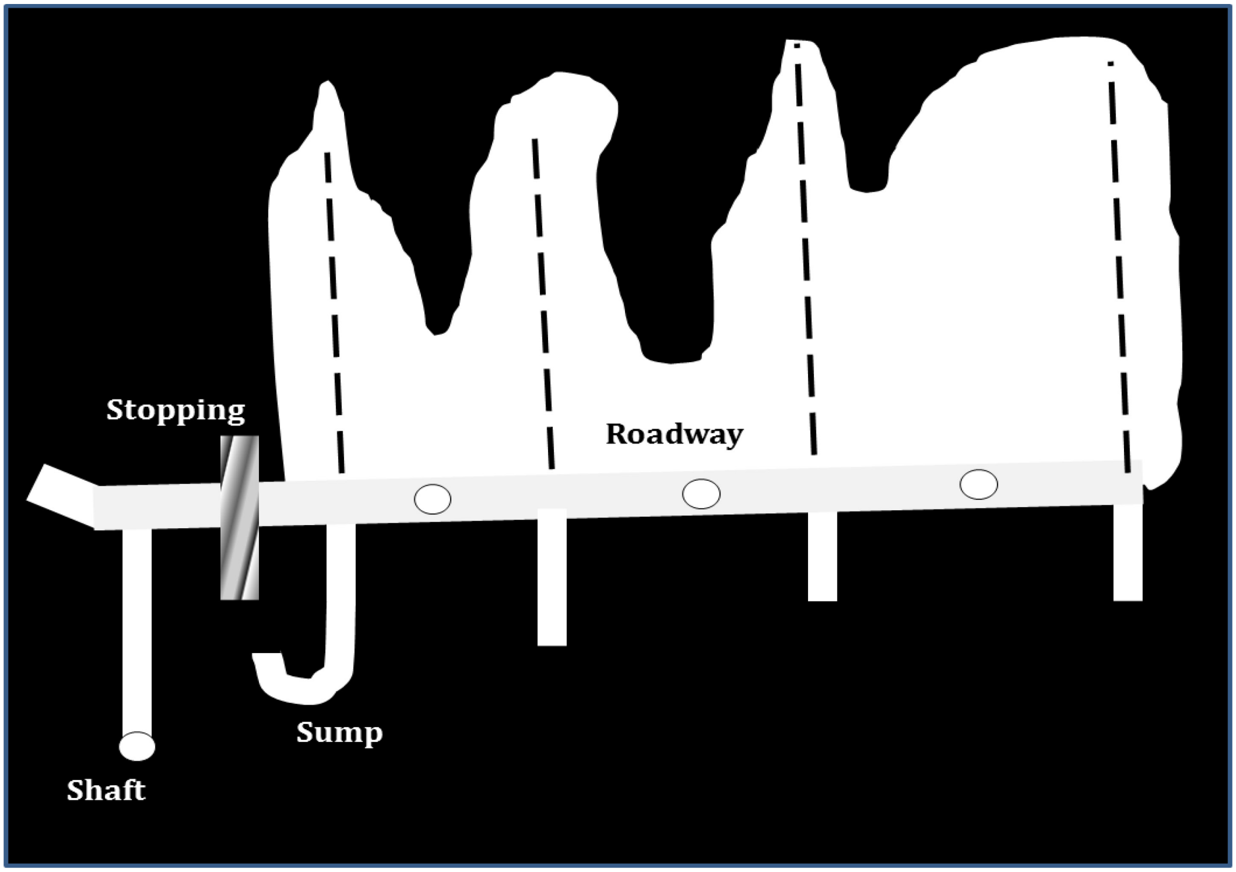


Figure 2.6: Voids left at termination, Newman Spinney

2.4 Current Developments

Currently the focus of research is to understand the behavior, dynamics and control of cavity growth, the thermodynamic changes during the process, heat inflow and out flow, flame propagation, linkage between injection and production well, synergies between UCG and CCS and burn cavity growth and process modeling [Hobbs, Radulovic et al. 1993; Blinderman, Saulov et al. 2008; Daggupati, Mandapati et al. 2010; Roddy and Younger 2010; Saulov, Plumb et al. 2010; Stanczyk, Smolinski et al. 2010]. Main technique used for UCG is Linked Vertical Wells (LVWs), consisting of two wells linked underground using high-pressure air, water or reverse combustion. Russians developed this technology and it was used at Chinchilla, Australia recently [Walker, Blinderman et al. 2001]. There are several variants of this technology. They all are based on difference in techniques to promote linkage between wells and include hydro fracturing, reverse combustion, in-seam borehole and CRIP (Controlled Retraction of Injection Point) configurations (Linear CRIP or Parallel CRIP). Figure 2.7 shows the idea of linked vertical wells.

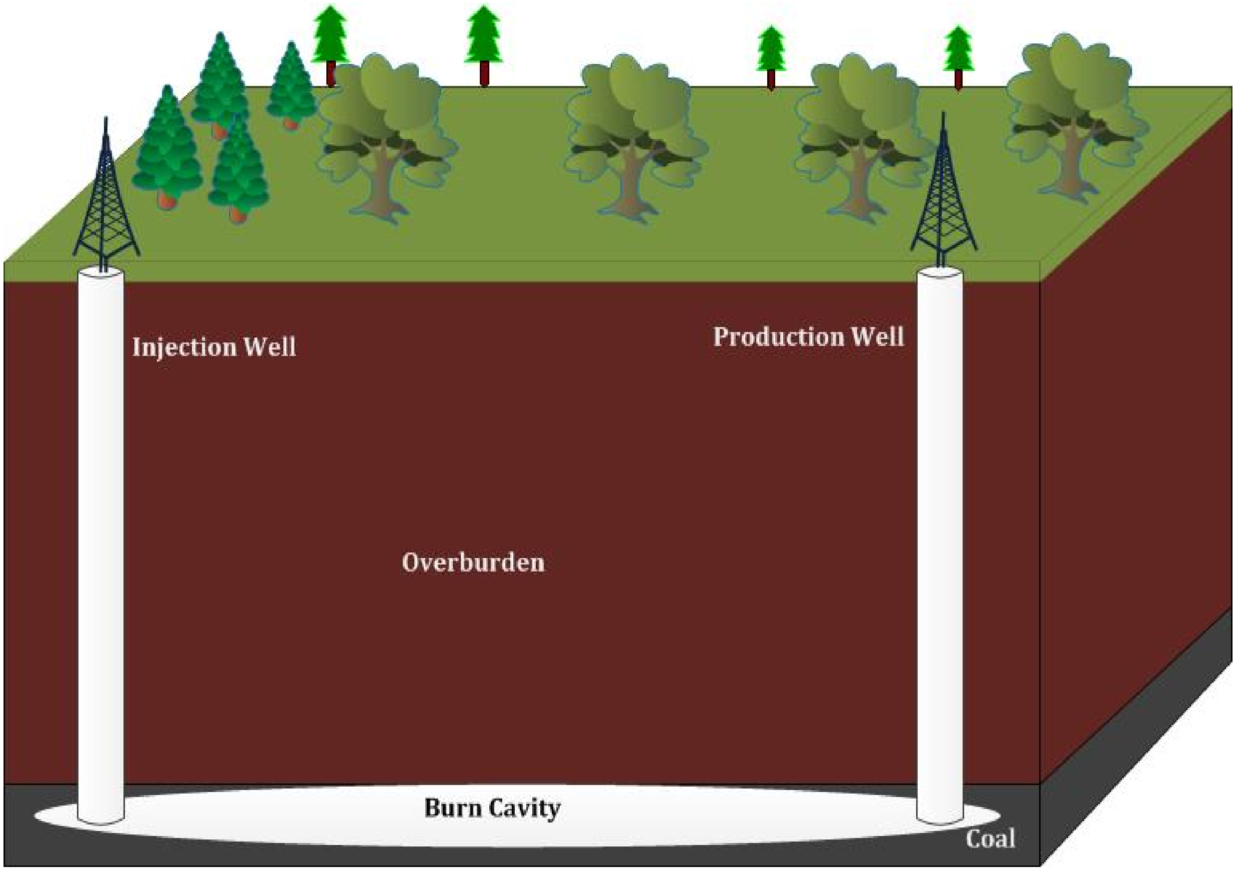


Figure 2.7: Linked vertical wells (LVWs)

Another approach developed for UCG application is to use man made excavations or using conventional mining entries like drifts, roadways and tunnels. It includes the chamber technique, used in China and referred as "undersurface gasification", a stream method developed from Soviet technique for steeply dipping seams and long tunnel, large section two stage (LLTS) method developed in China [Chen and Yu 1996].

2.5 Advanced Technologies

The Texyn "Santa Barbara" proposal involves using a physical gasifier at depths greater than 1000 m, injecting steam into the coal seam, shaping the cavity and withdrawing progressively as conventional CRIP [Couch 2009]. Another concept developed by the Polish is the super daisy concept that involves drilling blind holes from a shaft. Its layout is a shaft of 5.0 m in diameter and 300-400 jet stingers [Palarski 2007]. Another development is use of the CRIP method pioneered in the U.S. by Lawrence Livermore National Laboratory, during the trials in 1980s. It involves retraction of the burning front successively, thus exposing unreacted coal surfaces to oxidation and gasification [Clean Coal Limited 2007]. It has two variants, Linear CRIP and Parallel CRIP. This method is used in the Spanish trial by Linc Energy Ltd. and by Carbon Energy Pty Limited (CEPL) in Blood wood Creek with parallel holes [Carbonenrgy Ltd. 2011].

The Russians have designed a new technique for UCG development using in-seam boreholes and CRIP type operation [Couch 2009]. In the new technique, the in-seam borehole makes the linkages between the injection wells and the oxygen or air supply point moves and retracts successively like CRIP, thus improving gasification process.

2.6 UCG Chemistry

The process of burning coal with air or other oxidants involves complex series of reactions including carbonization, distillation, oxidation, reduction, pyrolysis, water-gas shift conversion, methanation and Boudouard reactions [Burton, Friedmann et al. 2006; Yang, Zhang et al. 2008].

- Oxidation reaction

$$C + O_2 \longrightarrow CO_2 + 393.8 \text{ MJ/kmol}$$

- Partial Oxidation

$$2C + O_2 \longrightarrow 2CO_2 + 231.4 \text{ MJ/kmol}$$

- Oxidation

$$2\,CO + O_2 \longrightarrow CO_2 + 571.2 \text{ MJ/kmol}$$

- Reduction/Boudouard reaction

$$C + CO_2 \longrightarrow 2CO - 162.4 \text{ MJ/kmol}$$

- Hydrogenous water-gas reaction

$$C + H_2O_{(g)} \longrightarrow CO + H_2 - 131.5 \text{ MJ/kmol}$$

- Shift conversion

$$CO + H_2O \longrightarrow CO_2 + H_2 + 42.3 \text{ kJ/mol}$$

- Methanation

$$CO + 3\,H_2 \longrightarrow CH_4 + H_2O + 206.0 \text{ kJ/mol}$$

- Hydrogenation Gasification

$$C + 2\,H_2 \longrightarrow CH_4 + 87.5 \text{ kJ/mol}$$

Figure 2.8 shows the schematic of the chemical reactions involved in UCG, adapted from Couch.

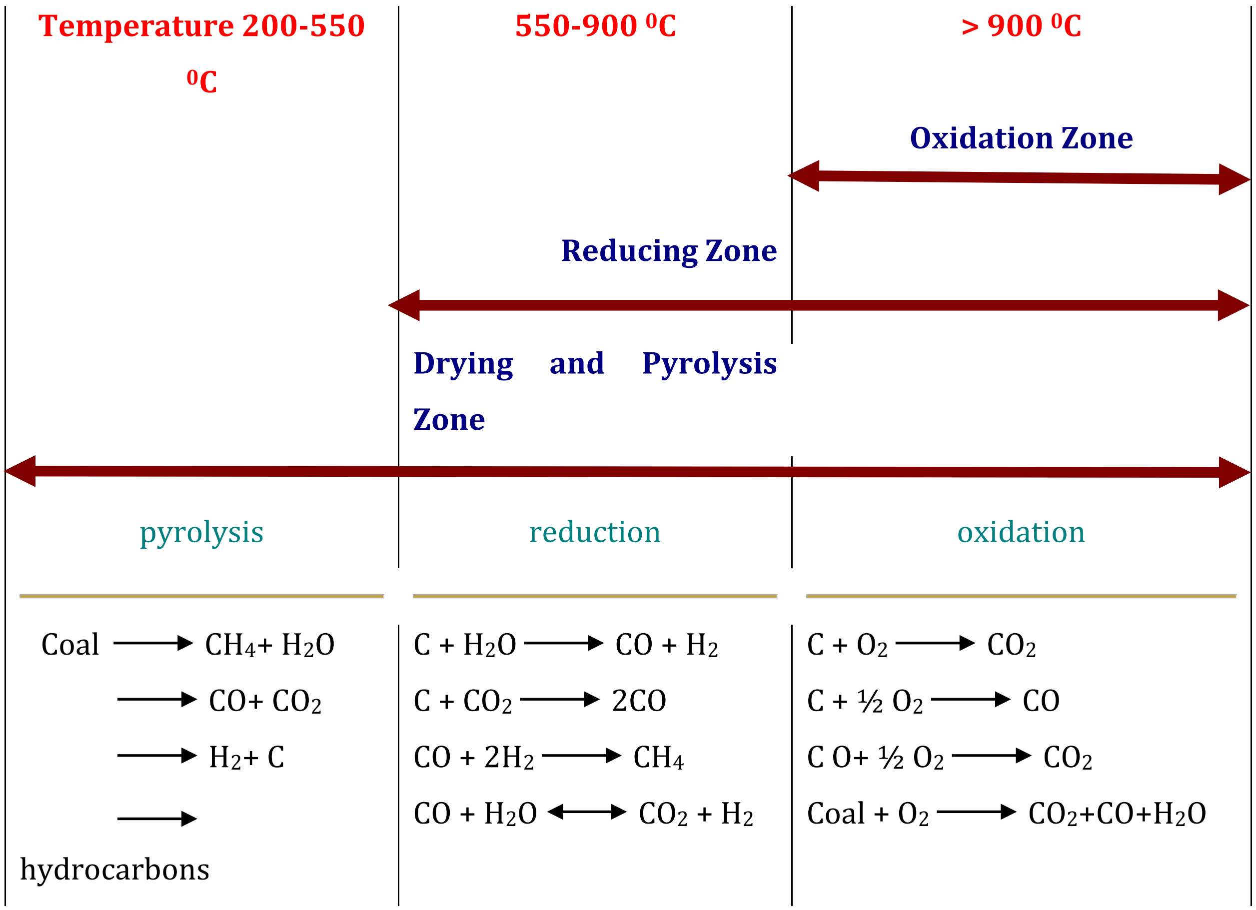


Figure 2.8: Schematic of processes involved in UCG

2.7 Benefits of UCG

UCG has distinct economic and environmental benefits over conventional coal mining, surface gasification and even coalbed methane drainage. There is a 20 times more energy yield from a given coal resource, when UCG is applied instead of CBM [Meany and Maynard 2009]. Creedy et al. suggest that as a method of exploiting coal, UCG represents a substantial environmental improvement on the combination of coal mining and surface coal combustion [Creedy, Garner et al. 2001].

2.7.1 <u>Economic Benefits</u>

UCG has the potential of exploiting coal resources, which are uneconomic for underground coal mining or are too deep to mine due to technical and safety restrictions. UCG can enhance workable coal reserves due to its applicability to deposits not minable through conventional mining methods such as coal deposits having low calorific values, deposits having thin seams or are steeply inclined or having thick seams that are deep seated [Lamb 1977]. That is why Burton et al. suggest a 300-400% increase in the recoverable coal reserves of the U.S. through application of UCG [Burton, Friedmann et al. 2006]. Although in the current market, natural gas is more attractive power generation source, in terms of cost and acceptability when compared to UCG, its reserves are finite and at some time in future, it will be more economical and strategically beneficial to replace or complement natural gas with UCG in power generation schemes [Creedy, Garner et al. 2001] .

Another economic benefit of UCG is reduced capital cost due to elimination of mining, transportation and storage of coal. There is no requirement of waste & ash management facilities and surface gasifiers. The syngas can be used directly as a fuel and feedstock for power generation and other chemical industries, after processing through onsite gas cleaning plant.

Another important advantage of UCG is its applicability to all kind of coals from lignite to anthracite [Burton, Friedmann et al. 2006] as demonstrated successfully in the surface gasifiers and also tested in UCG pilots and trials. However, some types of coals are easier to gasify than other types, for example swelling and coking coals can decrease permeability and porosity of coal upon heating. Low rank coals are preferred for gasification because they are generally shallow, easy to ignite and shrink on heating resulting in enhanced permeability and improved linkages between injection and production wells [Bialecka 2009]. This increases the economic viability of the UCG process as generally low ranked coals are given downgraded preference in the conventional mining. Though, the calorific value of syngas produced from lignite is generally in the lower range, several experiments have successfully resulted in the increased calorific value of syngas through the control of cavity geometry, burning process and type of oxidant used i.e. air, stream or oxygen [Hongtao, Feng et al. 2011; Stanczyk, Howaniec et al. 2011] .

UCG can work on any seam thickness, though it is preferable to have a seam thickness of more than 2.0 m [Burton, Friedmann et al. 2006]. As reported by Shafirovich and Varma, Ergo Exergy claims that coal seams as thin as 0.5 m may be gasified through UCG

[Shafirovich and Varma 2009]. However, thicker coal seams (>2 m) require fewer boreholes to gasify more amount of coal and provide economic and environmental advantages [Sury, Kirton et al. 2004].

UCG trials have been conducted on coal seams at varying depths, for example in Russia and U.S. coal seams as deep as 30 m to 350 m were gasified whereas in Europe, trials at much deeper depths (600-1200 m) were carried out [Shafirovich and Varma 2009]. At shallower depths, the problems of gas leakages and water contamination are more pronounced. At deeper depths, most of the aquifers are either saline or not potable, so the problem of aquifer contamination is reduced. Drilling at greater depths may increase the operating cost but new technological developments in drilling have made it possible to operate at greater depths without any technical and operational difficulties, generally faced in the past. New technologies and design solutions have promoted development of deep coal seams, increased control over rock pressures and reduction in the well requirements, thus decreasing drilling costs and encouraging UCG application to abandoned mines [Zorya, JSC Gazprom et al. 2009].

Seam inclination or dip is not a restraining factor for UCG site selection [Shafirovich and Varma 2009] and steeply dipping seams are preferred for UCG as they are considered less economical and technically difficult to mine through conventional mining methods as compared to horizontal seams [Lamb 1977]. Another potential economic benefit of UCG is its synergy with carbon capture and sequestration [Friedmann 2010].

2.7.2 Environmental Benefits

UCG possesses several environmental advantages as well. During the process, ash and heavy metals remain underground [Fergusson 2009], thus reducing cost and efforts for waste management. Sulfur and nitrogen come out to the surface with product gas but conventional sour gas cleaning technologies can remove sulfur from the gas [Fergusson 2009]. As reported by Meany and Maynard, ash content of syngas is one-seventh (1/7th) that of coal burnt on surface and various concentrations of toxic nitrogen oxides (NO_x) and sulfur dioxide (SO_2) are greatly reduced by UCG [Meany and Maynard 2009].

Due to elimination of mining, there is no overburden dump, no spoil dumps and no ash or tailing dams as most of the waste remain underground [Meany and Maynard 2009]. Creedy et al. have highlighted following environmental benefits of UCG over coal mining [Creedy, Garner et al. 2001]:

- Reduction in dust, noise and visual impact on surface
- Lower water consumption
- Lower risk of surface water pollution
- Reduced methane emission
- No Dirt handling and disposal at mine
- No coal washing and fines disposal at mine site
- No ash handling and disposal at power station sites
- No coal stocking and transport
- Smaller surface footprint
- No mine waste recovery and significant surface hazard liabilities on abandonment

Similarly, the process creates minimal surface disruption, thus resulting in reduced land acquisition and rehabilitation requirements [Ghose and Paul 2007]. Another important aspect of UCG is its synergy with carbon capture and sequestration (CCS). CO_2 is the main component of UCG syngas and may be present in the range of 25-40%. Integration of UCG and CCS may result in a critical climate change mitigation technology capable of producing power from coal and many studies suggest it as a low cost, above ground, low carbon form of coal power production [Redman, Fenerty et al. 2009]. The ideal scenario is to capture CO_2 from the product gas at the source and sequester it near the project site to avoid transportation cost. The technology to capture CO_2 from the syngas and to store it in the geological formations is readily available; however, research is in progress to store CO_2 in the voids and cavities created by UCG processes [Friedmann 2009; Roddy and Younger 2010].

An important environmental concern about UCG is its impact on groundwater. It can contaminate nearby aquifers through gas leakage and leachate [Sury, White et al. 2004]. The burning process results in organic pollutants like phenols, benzene, polycyclic aromatic hydrocarbons, and heterocyclic compounds and inorganic compounds like ammonia, cyanides, sulfates, and heavy metals [Humenick and Mattox 1978; Kapusta and Stanczyk 2011]. The amount and nature of contaminants depends upon the type and rank of coal (hard coal, lignite etc.) [Kapusta and Stanczyk 2011]. These pollutants can move out of the cavity either in aqueous phase or along with the gas leakage. However, this problem can be rectified through careful site selection, appropriate operation control, proper shut down process and effective environmental monitoring [Sury, Kirton et al. 2004]. In order to avoid flow of contaminations from the cavity to the underground water table and to minimize the loss of product gases, the pressure of burn cavity must be maintained below hydrostatic pressure, to ensure a small and continuous influx of water into the cavity to aid the burning process and to act as a barrier to contaminants outflow [Shafirovich and Varma 2009]. The Chinchilla project in Australia successfully demonstrated that UCG is an efficient, economic and environment friendly process to exploit energy from coal. A controlled shut down of the project in 2002-2003 revealed no ground water contamination, no surface area disruption, no observable subsidence and no gas leakage [Scott and Steve 2006].

2.8 Uses of UCG

The product of UCG is a gas at high temperature and pressure. This is a combustible gas and can be utilized for electricity generation in combined cycle gas turbine after minimal processing. After further processing and refining it can be used for production of a wide variety of gases, liquid fuels and chemicals [PWC. 2008]. Some uses of syngas are illustrated in the Figure 2.9 [Courtney 2009].

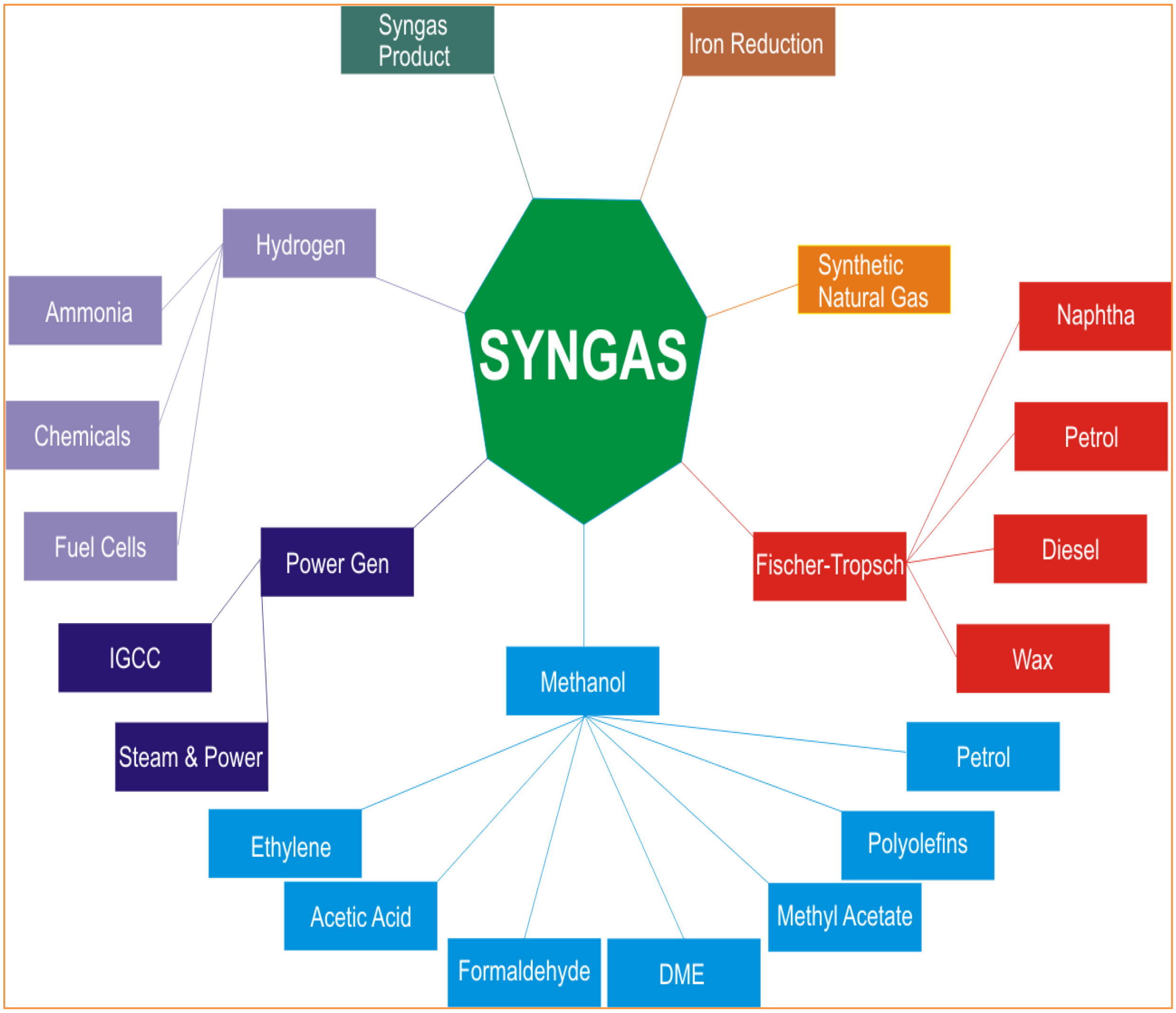


Figure 2.9: Syngas uses

Following is the list of possible syngas uses:

- Electric power
- Hydrogen
- Ammonia
  - Urea
  - Fertilizers
- Substitute natural gas

- Methanol
    - DME
    - Acetic acid
    - Formaldehyde
    - Gasoline
    - Olefins
- Other Chemicals
- Fischer-Tropsch liquids
    - Gasoline
    - Diesel
    - Jet fuel
    - LPG
    - Waxes
    - Lube oils
    - Higher alcohols
    - Chemicals
    - Naphtha
        - Petrochemicals
        - Solvents

Typical procedure includes gas cleaning before its application for other uses. Generally, the gas cleaning plant is proposed to be onsite to improve economic viability of the project.

2.8.1 Syngas

Syngas is the direct product of UCG. The composition of syngas is largely H_2, CH_4, CO and CO_2 [Ghose and Paul 2007]. The composition of UCG largely depends upon coal rank, geology, type of oxidants used (air, oxygen, steam) and process parameters. Syngas can be used directly as a fuel for boilers or electricity generators and as a feedstock for manufacturing of chemicals. The composition of raw product gas is similar to that produced by surface gasifiers, and cleaning technology for such gas compositions is already available [Creedy, Garner et al. 2001].

2.8.2 Electric Power

Syngas, if not transformed, is mostly used as a fuel for electric generation. The clean gas can be utilized in a gas-turbine based combined cycle power plant (IGCC). The integrated gasification combined cycle power plants are a matured technology and are in use worldwide. The IGCC power plants are being developed with the integration of carbon capture and sequestration (CCS) to reduce the greenhouse gas emissions [Cormos, Starr et al. 2010]. This means an IGCC plant based on UCG can provide all the benefits of IGCC power generation with the added advantage of eliminating coal mining and surface gasification plant [Walker, Blinderman et al. 2001].

2.8.3 Synthetic/Substitute Natural Gas (SNG)

Another important use of syngas is to produce methane (CH_4). Through the methanation process, syngas can be converted into methane or synthetic natural gas, which can provide an alternate domestic fuel supply utilizing the same infrastructure and end use equipment [PWC. 2008; Oukaci 2009]. The process to convert coal/ coal gas to synthetic natural gas is already developed and Dakota gasification company has been making SNG since 1980s [PWC. 2008]. This SNG can utilize the available pipeline networks for transportation to domestic and commercial consumers and can increase energy security especially in countries where natural gas deposits are less than coal deposits.

Two major chemical reactions for production of SNG are Methanation and CO shift reactions. These are exothermic reactions and can be used to produce steam [Oukaci 2009].

Methanation Reactions:

$$CO + 3H_2 \longleftrightarrow CH_4 + H_2O + \Delta H$$

$$CO_2 + 4H_2 \longleftrightarrow CH_4 + 2H_2O + \Delta H$$

CO Shift Reaction

$$CO + H_2O \longleftrightarrow CO_2 + H_2 + \Delta H$$

Figure 2.10 adapted after Oukaci, gives a simple overview of the SNG process [Oukaci 2009].

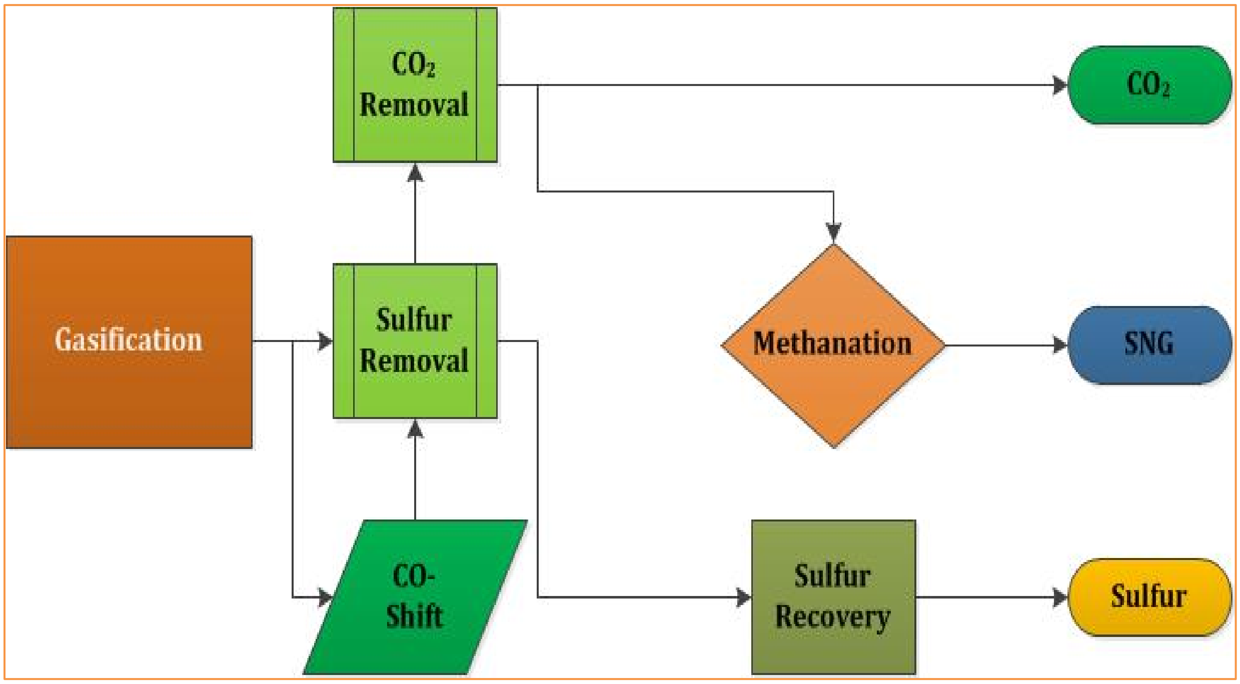


Figure 2.10: SNG process

2.8.4 Hydrogen Production

UCG provides an attractive source of low cost hydrogen production from coal. A paper by Yang et al. details the possibility of large-scale hydrogen manufacturing from UCG and indicates that backward gasification can increase gasification efficiency of coal seams and productivity of hydrogen, making UCG process feasible for large-scale H_2 production [Yang, Zhang et al. 2008]. A project in Shanxi Province of China utilizes UCG gas for the production of ammonia for fertilizers and high purity hydrogen [Burton, Friedmann et al. 2006]. This hydrogen is then utilized for industrial and commercial purposes. It is estimated that the cost of hydrogen from UCG syngas is roughly 2/3 that of other fossil fuel supplies and 1/6th that of electrolysis [Friedmann 2010].

2.8.5 Ammonia/Urea/Fertilizers

High purity hydrogen produced from syngas, can be catalytically reacted with N_2 to form anhydrous liquid ammonia and urea, which are the foundation of nitrogen-based fertilizers [Oukaci 2009]. Reaction starts with the blending of N_2 and H_2, resulting in partial conversion to ammonia.

$$N_2 + 3H_2 \longrightarrow 2\,NH_3$$

Then pure CO_2 is compressed and reacted with ammonia in the urea synthesis reactor to get product.

$$CO_2 + 2NH_3 \longrightarrow NH_2CO_2\,NH_4$$

$$NH_2CO_2\,NH_4 \longrightarrow (NH_2)_2CO + H_2O$$

A simple diagram after Oukaci, depicting process overview is given in Figure 2.11 [Oukaci 2009].

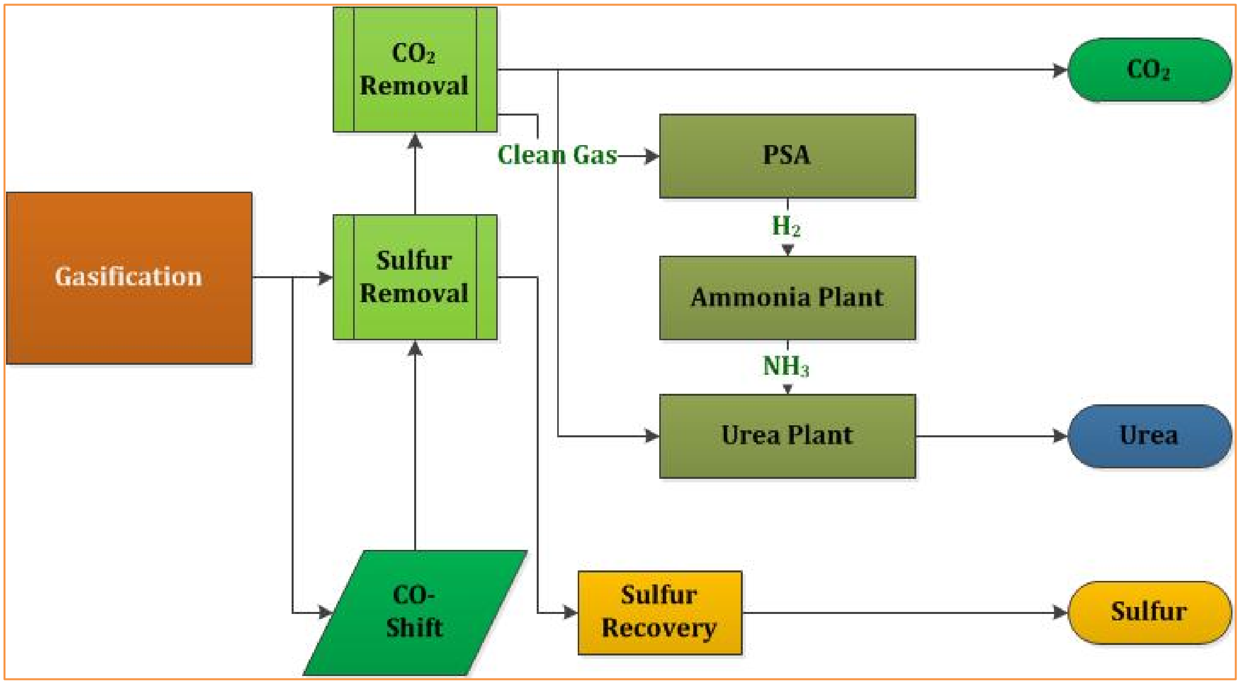


Figure 2.11: Fertilizer from UCG

In the U.S., Rentech Energy Midwest Corporation (REMC), a subsidiary of RenTech Inc. located in Illinois are in the process of converting their natural gas based fertilizer products plant to coal gasification based plant [RenTech Inc. 2009]. A pilot plant is already in operation in Shanxi, China producing ammonia fertilizers [PWC. 2008].

2.8.6 Methanol

Another valuable option for syngas utilization is methanol production. This can improve economic viability especially of small remote gas fields through utilization of syngas to produce a value added product. Methanol has several applications in the chemical and the fuel industries such as formic acid, acetic acid, formaldehyde and olefin. It can be blended into gasoline, converted into Dimethyl ether (DME) and may be used for power generation [Oukaci 2009]. It can be produced from syngas by the reaction of CO and H_2 in the presence of a catalyst (usually Cu, ZnO or Alumina).

$$CO + 2H_2 \longleftrightarrow CH_3OH$$

$$CO_2 + 3H_2 \longleftrightarrow CH_3OH + H_2O$$

The process overview is given below after Oukaci, in Figure 2.12 [Oukaci 2009].

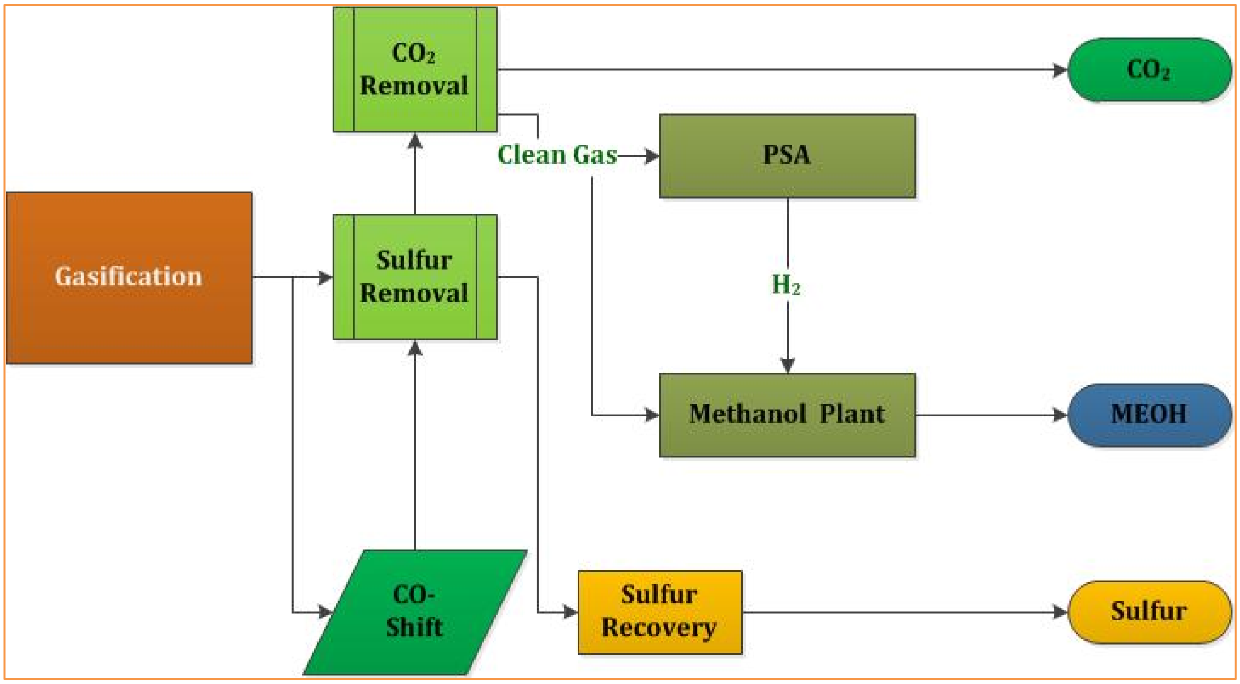


Figure 2.12: Methanol from UCG

2.8.7 Dimethyl Ether (DME)

DME, formed by the dehydration of methanol can act as an alternative fuel for compression-ignition (diesel) engines. It has the handling characteristics of LPG, completely sootless with 90% NO_x reduction and may compete favorably with conventional fuels [Oukaci 2009].

2.8.8 Gas to Liquids

There are two commercially proven technologies for conversion of coal into transportation fuels through gasification, Fischer-Tropsch process and Methanol to gasoline (MTG) process. Both technologies follow similar route to convert coal into liquids, with changing reaction conditions resulting into various products [ExxonMobil 2009].

2.8.9 Methanol to Gasoline (MTG)

ExxonMobil has developed a technology to convert Methanol to high quality, ultra clean compatible to refinery regular gasoline and commercially operated in New Plymouth, New Zealand [ExxonMobil 2009].

2.8.10 Fischer-Tropsch (F-T)

The Fischer-Tropsch reaction converts a mixture of hydrogen and carbon monoxide, derived from syngas in case of UCG, to liquid fuels. This process was discovered by German scientists and used to make fuels during World War II. SASOL in South Africa has been producing liquid fuels from coal for 30 years and many oil companies like Shell Oil, Chevron (Texaco) and Exxon Mobil have been conducting research on this process [NETL DOE. 2008]. UCG can provide feedstock for a F-T reactor and result in large amounts of aviation and diesel fuel [PWC. 2008]. F-T is a mature industry and does not require any specific distribution infrastructure, thus has market in the conventional fuel products [Oukaci 2009]. Utilizing syngas as F-T feedstock opens its doors for advanced technologies of converting syngas to transportation fuels, chemicals and domestic energy supplies.

2.9 UCG Worldwide

2.9.1 USSR

The former Soviet Union started research on UCG as early as 1930s. For next four to five decades, they reigned in this field. This technology matched their socialistic idea of reducing the burden and working hours of labor force. It eliminated extensive and painstaking underground mining and provided an effective source of energy. Lenin brought the idea of coal gasification into public perception and Joseph Stalin started an extensive research program [Klimenko 2009]. The first site was developed at Gorlovskaya in the Donbass but was abandoned due to World War II. A second site was started in Lisichansk in Donbass in 1935, reconstructed in 1949 [Olness and Gregg 1977].

In the 1940, the Russians started experimental work on brown coal at Tula in the Moscow basin. In the1960s several thousand people were involved in UCG production but the efforts declined rapidly in the 1970s due to the discovery of large natural gas resources [Olness 1981]. They did not abandon the work entirely but continued at much reduced rate. No new plants were set up during this period, however three stations were kept running. The work at Angren, now in Uzbekistan, started in 1959 and the site is still in operation [Brown 2012]. Similarly, Yuzhno-Abinsk, in Kuzbass Coalfield Siberia is also currently operational. The Soviet work demonstrated that UCG could be applied in any geological setting. They tried UCG on different coal ranks & types, thin to thick, shallow to deep and flat to steeply dipping coal seams [Fair, Larson et al. 1976].

In earlier trials, Russians tried to burn the coal adjacent to the roadways and drifts. But it resulted in the problems of air bypass and burning of much of the produced gas, hence they started to use the boreholes which proved very successful in overcoming these problems [Olness 1981]. Currently efforts are underway to bring UCG technology back in Russia and some projects are in pipeline. VNIIPromgaz R&D center is currently trying to revive the research in this field in Russia and implementing the technology abandoned by them to fulfill the energy demands of the country [Kreinin 2006].

2.9.2 The Europe

In several European countries, research on UCG continued between late 1940s and the 1980s, however major efforts for commercializing this technology started in the 1990s. The main efforts of these trials focused on application of this technology on high rank, deep coal seams, typical of Europe [Ag Mohamed, Batto et al. 2011]. Various trials took place in Belgium, France, Spain and the UK, a summary of which is given below.

2.9.3 UK

Sir William Ramsey planned the first test on UCG in County Durhum, UK in 1912. However, concrete efforts for UCG started in the 1940s when experimental work started at Newman Spinney, Derbyshire in 1949 and a second site opened at Bayton Worcestershire in the following year [Thompson, Mann et al. 1976]. In 1990s the UK government supported the European Union UCG research program in Spain and in 1999 started a new research and development program [Couch 2009]. Currently Clean Coal and British Coal Gasification (BCG) Energy Ltd are focused on developing deep coal reserves through the underground gasification of coal and the generation of power from syngas and natural gas [Courtney 2008]. Thornton New Energy, a subsidiary of BCG Energy Ltd, in January 2009 received the first UK license to carry out UCG and develop deep, previously un-minable coal reserves under the Firth of Forth, Scotland and recently Thornton New Energy and Waste2Tricity joined to convert coal into electricity combining new generation fuel cells with UCG [BCG Energy 2010].

2.9.4 France

In France, the work on UCG started in the late 1970s and continued until 1985 with experiments at Bruay-en-Artois and La Haute Deule, in northern coalfield. In these trials hydro-fracturing behavior, ignition characteristics and reverse combustion were analyzed [Clean Coal Limited 2008]. In another trial at Echaux near ST Etienne, electro-linkage was tried with limited success. Further development on UCG stopped because the experiments resulted in the blockage of production wells by the formation of tars, oxidation products and coal particles [Couch 2009]. No new developments have been reported in France since 1989.

2.9.5 Belgium

In Belgium, an experiment to gasify semi-anthracite was conducted in 1948, at Bois-la_Dame by Socogas. The coal seam was steeply inclined and the flame front advanced sideways from an inclined drift rather than upwards from a horizontal one and probably this approach contributed to poor results [Thompson, Mann et al. 1976].

In the 1980s, a UCG experiment was carried out at Thulin on a deep coal seam under the Belgian-German joint research project. The coal was semi-anthracite, non-swelling, multilayered with a cumulative thickness of about 6 m and depth of 860-870 m [Couch 2009]. A special drilling technique was used successfully to achieve linkage and CRIP was used in one of the test [Scott and Steve 2006].

Belgium was also part of the Spanish trial, carried out in 1992-1999 under the European Commission along with Spain and UK.

2.9.6 Spain

In El Tremedal Spain, UCG trial for deep underground coal seams was carried out as a joint venture between Spain, UK and Belgium under the European Commission. The trial was initiated at 1989 and finally abandoned in 1998. The trial evaluated the feasibility of UCG for coal seams at depths between 500-700 m. In this trial the CRIP process was used and linkage between wells was achieved by oilfield deviated directional drilling techniques [Clean Coal Limited 2008]. The Spanish trial provided the basis for several other trials in Europe and other countries, especially in the U.K. where the Department of Trade and Industry Technology took initiatives for the development of UCG technology [Scott and Steve 2006]. Another important aspect of the Spanish trial was implementation of the lessons learned from the U.S. trial at Hoe Creek. The underground conditions were kept close to hydrostatic pressure in order to avoid underground water influx and gas leakage through the strata [Creedy, Garner et al. 2001].

2.9.7 Other European Countries

In Europe, a large activity regarding UCG is going on. A project called “Hydrogen Oriented Underground Coal Gasification for Europe” or HUGE is underway under the European

Commission. Under the HUGE project, UCG trials will be carried out in an experimental mine called “BARBARA” [HUGE 2010]. Interest in Poland, Hungary, Bulgaria and other central European countries is growing and White Coal Energy & UCG Engineering Limited have UCG projects in Hungary and Bulgaria [Courtney 2008]. UCG Engineering Limited has contracts for UCG development projects in Eastern Europe and UK [UCG Engineering Ltd 2009]. Similarly Clean Coal Limited and UCG Partnership, in conjunction with other partners and research groups, are supporting research for UCG and are actively engaged in organizing conferences, seminars and workshops for promotion of UCG technology in Europe and other countries.

2.9.8 USA

The idea of gasification either underground or above ground, using mined coal has very long history in the U.S. and dates back to late 1800s when lamplighter used to make their rounds in larger cities, lighting streetlights fueled by “town gas” [Lawrence Livermore National Laboratory. 2007]. This “town gas” was crude form of coal gasification and disappeared when large reserves of natural gas were discovered [Lawrence Livermore National Laboratory. 2007]. In the late 1940s a small test was carried out at Gorgas, Alabama but the main program started in 1973 [Klimenko 2009]. The main sponsor for this program was the U.S. Department of Energy (DOE) with some industrial partnerships. During 1973 to 1989, more than thirty tests were carried out with the focus on specific engineering concerns such as improvement in the linkages between wells and the permeability of coal [Couch 2009]. This $ 350 million program was a technical and environmental success but it could not reach commercialization, partly because of dramatic drop in oil and natural gas prices in the mid-1980s [Friedmann 2010]. The U.S. DOE program was a well-planned series of trials aimed at exploring the performance and behavior of UCG reactors. The tests investigated the effects of using different oxidants (oxygen, air, steam) on syngas quality and yield, evaluated the proper shutdown process and resulted in the development of CRIP process used in Centralia, Washington and rocky Mountain 1 in Wyoming [Couch 2009]. Following is a summary of DOE trials given by Davis [Davis and Beath 2006];

- Hanna, Wyoming, conducted by Laramie Energy Technology Center on sub bituminous coal in 1971-1981
- Hoe Creek, Wyoming, conducted by Lawrence Livermore National Laboratory on sub bituminous coal in 1972-1982
- Morgan Town, West Virginia, conducted by Morgantown Energy Technology Center on bituminous coal in 1976-1982
- Centralia, Washington, conducted by Lawrence Livermore National Laboratory on sub bituminous coal in 1981-1985
- Rocky Mountain 1, very close to Hanna site, conducted by an industrial consortium led by Gas Research Institute on sub bituminous coal in 1986-1993

The trials financed and led by industrial consortiums include the following [Davis and Beath 2006]:

- Rockdale, Texas, led by Texas A&M University on lignite in 1978-1980
- Rocky Hill, Wyoming, led by Atlantic Richfield Co on sub bituminous coal in 1977-1982
- Tennessee Colony, led by Texas Utilities on lignite in 1976-1980

Though not all these test were completely successful, as some of these resulted in the contamination of potable aquifers especially in Hoe Creek and Carbon County Wyoming, they provided very useful information about the engineering, technical and environmental aspects of the UCG operations. One of the major contributing factors in the failure of UCG pilots in Hoe Creek and Carbon County Wyoming, USA, was poor site selection [Clean Air Task Force 2009]. These projects resulted in the contamination of potable ground water and seriously hampered further developments of UCG in the U.S [Klimenko 2009] . Although the U.S. DOE heavily funded the pilot researches in the 1970s and 80s, the resulting environmental impacts blocked further funding into UCG. Another factor in the abandonment of UCG trials was availability of cheap oil and natural gas in the 1980s [Friedmann 2010].

UCG research in the U.S. has resulted in the following contributions [Creedy, Garner et al. 2001]:

- Cavity growth modeling concepts
- Development of CRIP
- Guided drilling techniques to establish gasification channel
- UCG application on bituminous coal
- Environmental impact data of UCG
- Importance of hydro-geological characterization

UCG efforts are reviving in the U.S. and several private companies and industrial organizations are promoting research in this field. In 2006, DOE commissioned Lawrence Livermore National Laboratory to evaluate the status of UCG technology. They prepared a draft report “Best Practices” in 2006 and updated recently. They are also developing a detailed model of contamination flow and transport specifically for UCG [The Working Group on UCG 2007].

2.9.9 China

China has the largest UCG program currently underway with at least 16 trials carried out since the late 1980s [Brown 2012]. Coal is the most important energy source in China and there are nearly 300 abandoned mines and with some 30 Gt of coal resources [Couch 2009]. In China, the UCG is applied on abandoned mine galleries with access gained through existing workings, in order to recover the remnant coal from mines. The China University of Mining and Technology, Beijing has developed a long tunnel, large section, two-stage method for UCG production capable of producing gas with the heating value in the range of 12-14MJ/m^3. There is a UK-China technology transfer project in progress for the development and commercialization of UCG [Creedy, Garner et al. 2001]. XinAo group is working on a UCG project on sub bituminous coal in China. The group is planning to setup a methanol plant based on UCG syngas feed [Wan and XinAo Group 2006].

2.9.10 India

The Oil and Natural Gas Corporation Limited (ONGC) discovered large reserves of about 350 billion tonnes of coal at depths more than 600 m in Gujarat and Bengal and the prevailing geological, hydro-geological and strata conditions favor the use of UCG for exploitation of these reserves [The Working Group on UCG 2007]. The ONGC and the Gas Authority of India Ltd. (Gail) have prepared feasibility of UCG on pilot basis and ONGC have signed a Memorandum of Understanding with the Skochinsky Institute of Mining (SIM) of Russia and Coal India Limited (CIL) for a UCG pilot study [Khadse, Qayyumi et al. 2007]. Indian government is in the process of making the policy to designate blocks for UCG in order to facilitate the application of this technology [Khadse, Qayyumi et al. 2007]. The Australian government is also supporting UCG development in India and helping in the preparation of feasibility for UCG application in Andhra Pradesh. Cougar Energy Limited has signed a UCG contract with Essar Exploration and Production Limited (EEPL) for UCG development in India [Walker 2008].

2.9.11 South Africa

South Africa has been using coal to liquid technology since 1955, with most of this work confined to surface gasification but is now promoting research to use low grade, unminable coals for power generation and liquid fuel manufacturing through UCG [PWC. 2008]. Sasol, South Africa is planning to invest in a pilot plant to investigate the commercial viability of UCG in the CTL (coal to liquid) process [Hattingh 2008]. Another South African Company Eskom, has developed a UCG pilot plant at Majuba Colliery to prove the ability of co-firing with coal at Majuba power station [PWC. 2008]. This was the perfect location for UCG pilot as the sub bituminous coal at mine cannot be mined conventionally [PWC. 2008]. On 28th October 2010, Eskom's UCG demonstration plant delivered gas to Majuba Power Station, and co-fired with coal to produce 3MW electricity [Eskom 2010]. This was the first commercial production of electricity from UCG after the Soviet program.

2.9.12 Australia

In Australia, several projects are underway to establish the commercial viability of UCG. The Chinchilla project is a milestone in the commercial development of UCG. As a joint venture of Linc Energy Ltd. and CS Energy Ltd., a pilot plant started in 1999 at Chinchilla, 350km west of Brisbane [Walker, Blinderman et al. 2001]. The burn started initially at three process wells and expanded to eight operating wells [Walker, Blinderman et al. 2001]. The project ran from 1997 through 2003 with a controlled shutdown and restart and was the largest in the West [Burton, Friedmann et al. 2006]. Ergo Exergy Technologies Inc. provided the technology for the project and designed the UCG plant, under an agreement with Linc Energy Ltd [Linc Energy]. This project demonstrated that UCG could provide commercial quantities of industrial gas for power generation at an economically viable price to ensure the competitiveness of coal based IGCC in the market [Walker, Blinderman et al. 2001]. Linc Energy Ltd also planned to develop a small coal to liquid (CLT) plant with the support from Syntroleum Corporation, a Fischer-Tropsch technology provider [Davis and Beath 2006].

Currently Cougar Energy Ltd is working on a 400 MW project at Kingaroy Queensland, as well as UCG projects at Wandoan Queensland and Latrobe Valley Victoria, in Australia [Cougar Energy 2010].

2.9.13 Pakistan

Pakistan has estimated coal reserves of about 185 billion tons, out of which 175 billion ton reserves are located at Thar in the southern part of Sindh province. The coalbed thickness in Thar ranges from 0.20-22.81 m with multiple seams reaching up to a maximum of 20 seams at some places with cumulative thickness of 36 m [Sindh Coal Authority 2005; Thar Coal & Energy Board 2008] . The coal ranges from Lignite-B to sub-bituminous-A with high moisture and low sulfur contents. Thar coalfield is part of Thar desert, covered by sand dune that extends to an average depth of over 80 m and overlies alluvial deposits containing sandstone, siltstone & claystone reaching up to 209 m [Sindh Coal Authority 2005]. Government of Pakistan is planning to apply UCG for exploiting Thar coal and has taken several steps in this regard. A pilot plat to produce 50 MW electricity from Thar coal through UCG is in progress and the first stage of UCG pilot is expected to be operational in May 2011. Cougar Energy Ltd., Oracle Coal Fields Ltd. and China Petrochemical Corporation

(Sinopec) are also conducting feasibility studies for UCG in Thar and hold leases in that coalfield [Srivastava 2011].

2.9.14 Others

Several other countries are interested in UCG development and either pilot projects or feasibility studies are underway. Those examining UCG potential include, Bulgaria, Former Czechoslovakia, Italy, Morocco, Oman, Poland, Romania, Thailand, Brazil and Turkey [Creedy, Garner et al. 2001]. Clean Coal Limited and Linc Energy Limited have signed MoU for UCG development in Indonesia and Vietnam respectively [Courtney 2008].

2.10 Challenges

UCG is a method that requires proper environmental management. Major environmental problems with UCG include ground water pollution and subsidence. UCG may also create hazards of atmospheric emissions and human impact such as noise, increased traffic and dust [Creedy, Garner et al. 2001]. Sulfur and nitrogen also rise to the surface along with product gas [Fergusson 2009]. Similarly, CO_2 management may pose problems if the process is not adequately planned. Although UCG is not a new technology, it is still a developing technology and requires many research and development initiatives for realization of its commercial potential. Research about environmental, economic and technical aspects of UCG is needed to prove its maturity as a viable coal exploiting technology in comparison to other competitive energy sources like CBM, natural gas, surface gasification and conventional coal mining. These challenges provide opportunity for the advancement and growth of this technology to provide its share in the energy mix.

Chapter 3 – Operational Parameters of UCG

3.1 Ignition

Ignition of coal seam generally starts after the wells have been drilled and gasifier is ready to operate. Several methods can be used for insitu ignition of coal seam but the most popular method is utilizing electrical resisting heating. In this method, two electrical lighters (generally 1 Kw) are lowered into the well along with a thermocouple that measures the changes in the temperature [Thorsness, Hill et al. 1977]. After the lighters are lowered in the well close to the coal seam, charcoal briquettes, wood chips or other flammable material is placed at the bottom of the hole until the lighters are covered with this material. At this moment, the controlled flow of air is directed at the lighters and charcoal. The charcoal and wooden chips ignite in a few minutes and in turn ignite the coal seam. This is demonstrated by changes in temperature indicated by the thermocouple. Once the ignition has started, the gasification process starts and the injection of gases and steam starts at the rate and pressure designed for the particular gasifier.

Another method used for initial ignition of coal seam is through explosive material. In this method, propane, gasoline or lighting fluid is injected into the coal seam just prior to start of ignition and a light explosive charge is exploded at the bottom of the hole. The flame generated by the explosion starts the fire that is sustained through the injection of oxygen or air. Wooden chips or other flammable material can also be dumped into the hole, if required.

3.2 Wells Pattern

Generally, four types of wells are drilled to form the gasifiers. They are

i. Injection wells
ii. Production wells
iii. Instrumentation/monitoring wells
iv. Dewatering wells

Injection wells are used for injecting the oxidizers i.e. air, gas or steam into the seam. They have compressors or compressing stations installed around them and inject high-pressure gases into the gasifiers. The production wells are used to extract the syngas form the gasifier. The injection and production wells are sometimes collectively referred as process wells [Blinderman and Jones 2002]. The instrumentation wells are scattered in the area as per design of the cavity. They contain instruments for measuring pressures, temperature and flow rates and monitoring the flows in or out of cavity. The dewatering wells are used to dewater the seam either prior to gasification or during the gasification process. These wells are also used to collect samples for measurement of water quality prior to, during and after the gasification process.

3.3 Wells Spacing

The spacing and number of process wells in the gasifier depend upon coal thickness, coal rank, geology of the area i.e. number of prominent fractures or folds in the area, permeability of the coal seam, gasification rate and economics of the project. Number of wells requirement for thicker seams is less as compared to number of wells required for thinner seams, thus in thicker seams wells can be at greater spacing than those in thinner seams. Most common well spacing lies between 18 m (60 ft.) to 30 m (~100 ft.). The increase in well spacing decreases the drilling cost and price of gas. A sensitivity analysis of well spacing and cost of gas however indicates that the cost benefits decrease rapidly after the well spacing is more than 150 feet [Boysen 1978]. The reason is contribution of drilling cost to the operating cost, which has reduced impact after this spacing. Monitoring wells are generally placed around 15 m and 30 m radius [Snoeberger 1977].

3.4 Wells Structure

The process wells are generally steel cased and cemented to withstand the higher temperatures and pressures. These wells can be completed in the upper portion of seam and perforated at the lower or bottom part of the seam [Fischer, King et al. 1977]. The diameter of process wells is in the range of 14 to 20 inches [Boysen 1978]. The instrumentation wells are generally not cemented or cased and are small diameter holes.

They carry thermocouples and tubes for measuring temperatures, water levels and gas sampling. The dewatering wells are steel cased to the top of coal seam and are perforated within the coal seam and have steel pump sections that carry water pumps to collect water from sumps [Thorsness, Hill et al. 1977].

3.5 Instrumentation

The instruments are used to measure temperatures, air and gas pressures, water level, flow rates, and for gas sampling. Thermocouples are used to measure the temperature variations within the coal seam and in the surrounding strata. A single instrument hole can carry several thermocouples at different depths. They are generally placed within the seam at varying depths (top, center and bottom of seam) and at 5, 10, 15 and 20 feet in the over and under burden to have complete temperature profile of the gasifier and surround rocks [Thorsness, Hill et al. 1977]. The air and gas flow meters, transducers and gas chromatographs measure the flow rate, pressure and composition of gas. Submersible pumps are used in dewatering wells.

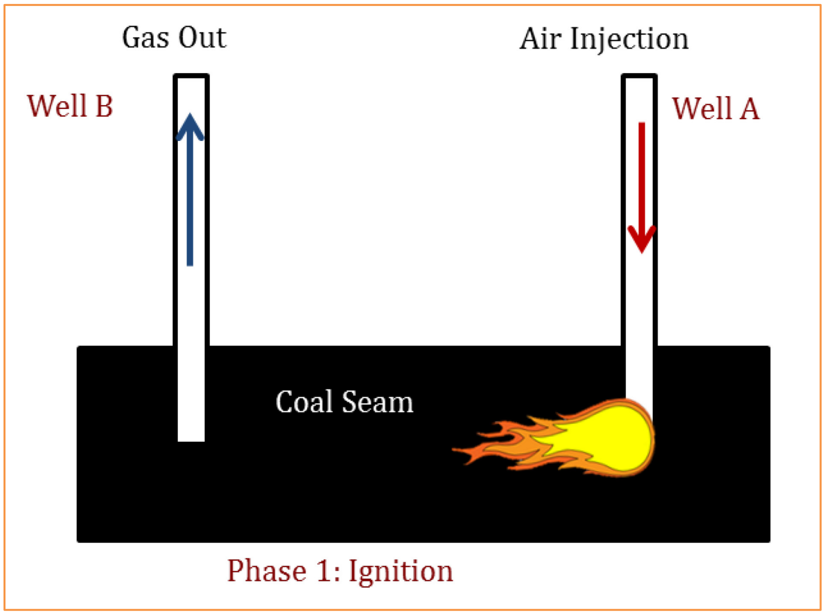
3.6 Well Linkages

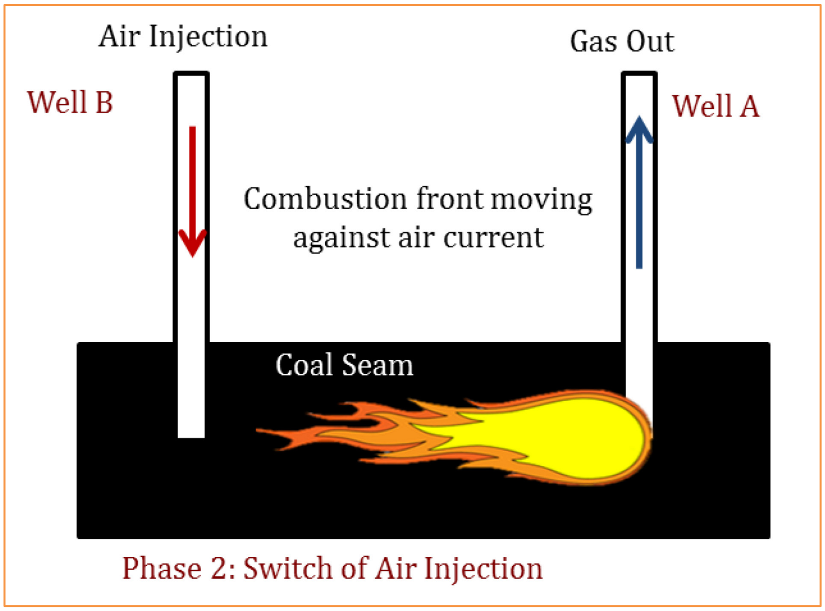
The most important step during the creation of insitu gasifier is the development of linkage between the injection and production well. This can be achieved through any of the following method.

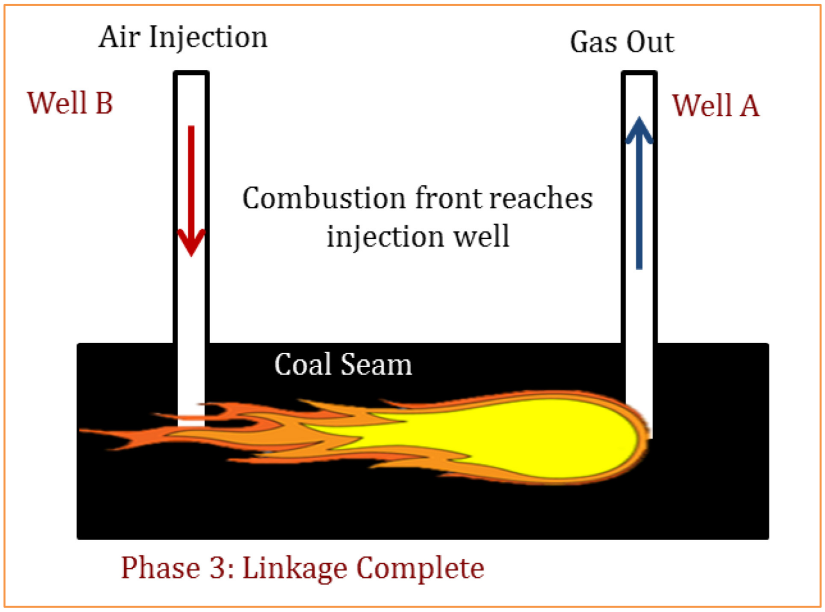
i. Explosive fracturing
ii. Reverse combustion linkage
iii. Hydraulic fracturing
iv. In seam channels through drilling
v. CRIP (Controlled Retraction Injection Point)

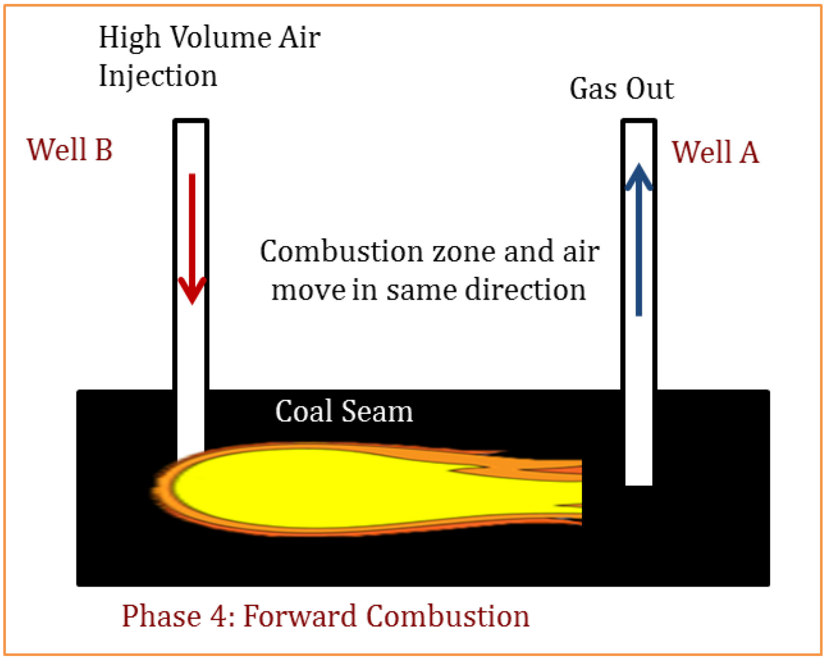
In the explosive fracturing technique, high explosive is detonated at the bottom of the hole, either in one of the process wells or at a specially drilled well for this purpose. The idea behind this technique is that explosive fracturing will enhance the permeability of the coal, hence the linkage between the wells. An experimental blast consisting of two high explosive spherical shots at Hoe Creek Wyoming revealed that this technique creates three regions after explosions [Thorsness, Hill et al. 1977]. The region where there is no change in the permeability and the permeability value remains as it was before explosions. This region is at a radial distance of about 50 feet from explosions depending upon type of explosive and geology of the area. A very high permeability area within 10 feet of explosive charges and an intermediate area where permeability is significantly enhanced after explosions. However, this technique is not very successful as in the areas very close to explosion, the permeability actually decreased due to plugging of fractures by fine coal particles resulting from the blast [Thorsness, Hill et al. 1977].

Reverses combustion linkage is somewhat more successful method than explosive fracturing and has been tried in several experimental trials and pilots in the Europe, the U.S. and other places [Zamzow 2010]. In the reverse combustion linking, the fire is started at one well, well A in Figure 3.1. The air is initially injected in the ignition well (well A) to sustain the fire. Once the combustion of coal is started, the air injection is switched and injected to the other well, well B in Figure 3.1. Now the air current moves towards the ignition front through the coal seam and the combustion moves from ignition well (well A) to the injection well (well B). The combustion zone is moving against the current of air towards oxygen source (well B) and because of this movement against the air current, the process is called reverse combustion. Because of this movement of combustion zone towards injection well, a highly permeable localized zone is created in the seam. After the combustion zone reaches the injection well, the reverse combustion is completed [Fischer, King et al. 1977]. At this point high volume, low-pressure air is injected into the injection well (well B) and combustion zone now moves towards ignition well (well A). At this point air current and combustion zone move in the seam direction and this is called forward combustion. The position of reverse combustion link at the bottom of seam is very important, as in the forward combustion this undercut zone will result in falling of fresh coal in the reaction zone, yielding high efficiency and producing a packed bed [Fischer, King et al. 1977].


Gas Out
Air Injection
Well B
Well A
Coal Seam
Phase 1: Ignition


Air Injection
Gas Out
Well B
Well A
Combustion front moving against air current
Coal Seam
Phase 2: Switch of Air Injection


Air Injection
Gas Out
Well B
Well A
Combustion front reaches injection well
Coal Seam
Phase 3: Linkage Complete


High Volume Air Injection
Gas Out
Well B
Well A
Combustion zone and air move in same direction
Coal Seam
Phase 4: Forward Combustion

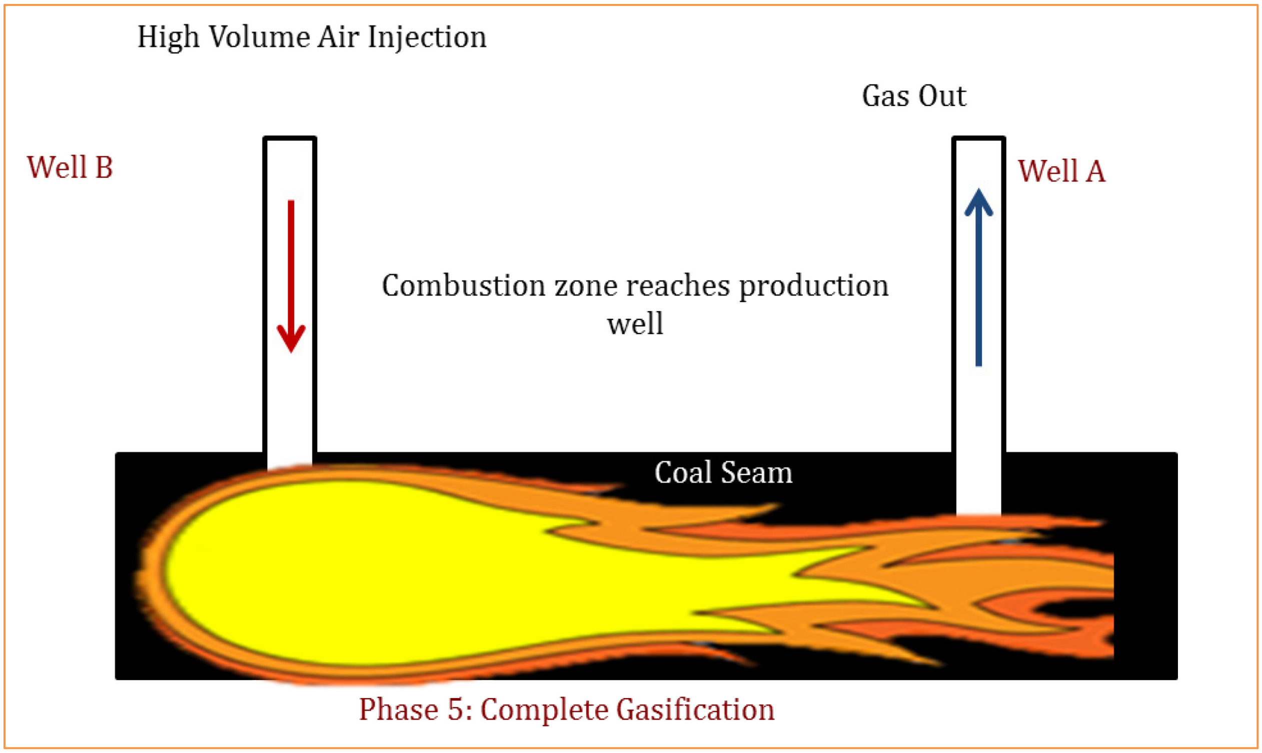


Figure 3.1: Reverse combustion linkage

Hydraulic fracturing is another technique used to improve the linkage between wells. In this process, the low-pressure water is first used to washout the borehole. The pressure is then increased gradually until the cracks are generated in the seam. After that, hydraulic fluids are pumped into the cracks. Finally the area is flushed with water and then with air to remove any plugging [Olness 1981]. The control in hydraulic fracturing is very important, as the process can increase the potential of gas losses greatly due to irregularity of fractures development.

In-seam channels are one of the better options to improve well linkages. In this method, an in-seam cannel is created by drilling a horizontal borehole in the lower part of coal seam. Directional drilling reduces the surface disruption and increases the amount of coal that can be accessed by a pair of wells [Ahner 2008].

The CRIP technology is a modern technique, giving excellent control in the cavity formation and linking the wells and is based on advancements in directional drilling. CRIP stands for Controlled Retraction of Injection point. In this technique, the injection point is retracted occasionally to expose the fresh coal to the injecting gases. In this method, the link between the wells is established through a directionally drilled horizontal borehole between the injection and projection well. After a cavity has been formed in the coal at a specific location, the injection point is retracted either mechanically or by burning the portion of the injection tube, thus exposing the fresh coal to the stream of gases and developing a new cavity. 10 to 20 such movements can occur during the lifetime of a set of wells [Clean Coal Limited 2007].

3.7 Operating Pressures

The operating pressure required for gasification depends upon the type of coal, the permeability, depth of seam, type of oxidant used, amount of water and moisture in the coal and strata, and most importantly the hydrostatic pressure around the burn cavity. The experiments in the U.S. dictate that the operating pressure should never exceed the hydrostatic pressure of the cavity, otherwise the hazardous waste and pollutants can migrate out of the cavity and can result in the contamination of surrounding area and water resources [Ahern and Frazier 1982; Younger, González et al. 2010]. The air pressure also depends upon the method used for linking the wells. For reverse combustion and hydraulic fracturing high pressure is required to move the ignition front whereas low pressure is required for CRIP and in-seam borehole. The gas pressures at the beginning of ignition are high to promote combustion of coal, but once combustion is achieved, injection pressure is reduced and flow rate is increased. Typical injection pressures range between 60 to 120 psi and the flow rates vary from around 200 scfm in the beginning to around 4500 scfm at various stages of gasification [Fischer, King et al. 1977].

3.8 Cavity Development

After ignition, the cavity starts to develop along the line of linkage between the wells. In case of reverse combustion linkage, the cavity develops in the form of a cylinder with the final radius almost equal to the distance between the process wells [Fischer, King et al. 1977]. The initial development of cavity is in the horizontal direction but later the cavity developments occurs in a vertical direction and burning g takes place near the top of seam [Roehl, Brown et al. 1977]. Thus, the initial linking path should be close to the bottom of the seam during reverse combustion to get maximum recovery in forward combustion. For directional drilling and CRIP, the cavity develops around the borehole and expands laterally.

3.9 Water Control

Water plays a crucial role in the gasification process. The presence of water affects the nature and quality of the product gas [Walters and Nuttall 1977]. The presence of water is necessary for sustaining the reaction and water inflow of about 1 gpm is considered good for gasification [Snoeberger 1977]. The water inflow depends upon the presence of aquifer in the area and permeability of the seam. In high permeability area, the water influx can be higher than the desired levels and can decrease the heating value of the gas, as vaporization of the water consumes part of thermal energy. Excessive water influx can be controlled by using the dewatering wells, controlling the cavity or gas pressure, gasifying the seam in an up dip direction and two-stage pyrolysis gasification[Gunn 1977; Vanderborgh, Wewerka et al. 1977] . In the two-stage gasification pyrolysis process, CO_2 is recovered from the product gas, heated and injected into the coal seam prior to gasification in that portion. This heated CO_2 dries the coal seam, thus resulting in less water contents and increased porosity of coal because of the water removal from pores [Vanderborgh, Wewerka et al. 1977] .

3.10 Gas Cleaning

The level of cleaning required for product gas depends upon the amount of sulfur compounds, moisture contents, particulate matter and gas composition. Sulfur and nitrogen report to the surface with the product gas but sulfur can be removed using sour gas cleaning technologies that are already available and quite common [Fergusson 2009]. The CO_2 removal from syngas stream is quite easy and economical and technologies are currently available to separate CO_2 from syngas either onsite or at power plants in a cost-effective manner [Clean Air Task Force 2009]. The gas stream exiting the production well is at elevated temperatures and gas cleaning is accomplished more easily if the gas is at lower temperatures [Vanderborgh, Wewerka et al. 1977]. This is achieved through the introduction of a heat exchanger in the system before transporting gas to the gas cleaning facility. If the gasification is taking place at lower depths and the pressure of syngas is less than the operating pressures required for turbine, a compressor can be inducted into the process line to pressurize the gas at desired levels [Blinderman and Jones 2002]. However, for gasification of deep-seated coal seams, the compressor is not required as product gas is already at elevated pressures. Cleaning of product gas from UCG is easier and relatively less expensive than that from the surface gasifiers because the more viscous coal tars from surface gasifiers plug the valves and other equipment, whereas tars form UCG have low viscosity similar to that of oils [Gunn 1977] and are easy to remove for gas cleaning.

3.11 Economics of the Process

The economics of UCG largely depend upon the type of coal, depth and thickness of coal seams, number and diameter of wells, well completions type and extent, the linking technique used, type and amount of oxidant used, gas pressure, quality, heating value, leakage, subsidence, water influx rate, type and size of compressors used, gas cleanup requirements, type and number of instruments and conversion and recovery efficiencies. Seam thickness and well spacing have more pronounced impact on gas prices as compared to other variables [Boysen 1978]. The cost of syngas is comparable to very low cost thermal coal and the cost of electricity generation from syngas is very competitive to coal fired power stations. The capital cost of UCG_IGCC is almost half of that for coal-IGCC plant as no surface gasifier is required and UCG-IGCC can produce electricity at a price as low as \$10.00/MWh [Blinderman and Jones 2002]. A detailed economic analysis by Indiana University for UCG application to Indiana Coal indicates that production cost for UCG based on air as oxidant is \$8.04 per MMBtu and for oxygen oxidant, this cost drops to \$ 4.8/MMBtu. The cost of electricity production at combined cycle plants is \$ 0.0863/KWh for air-fired UCG and \$.0643/KWh for oxygen-fired UCG [Ag Mohamed, Batto et al. 2011]. The carbon capture and sequestration adds 1.7 cents per kilowatt hour and makes UCG more economical than competing technologies in the case when carbon tax or cap and trade is imposed [Ag Mohamed, Batto et al. 2011].

3.12 Chapter Conclusions

In this chapter, the operational parameters of UCG are evaluated. Cavity pressures, gas and water flow rates and linkage between process wells are the most important parameters that help in the continuous flow of consistent quality product gas and depend upon strata conditions and coal quality parameters. The improvements in the well linking techniques have made it possible to have a constant control of cavity development, gas flow and quality of gas. The monitoring of contaminant movements and environmental impacts of cavity development and gas flows is very essential to control the environmental impacts of UCG. With the advent of sophisticated equipment and reliable online systems, monitoring of UCG process is improved and can be done remotely. Improved understanding of the process through experiments and pilot studies has helped in the evolution of better process and operational controls.

Chapter 4 – Development of Site Selection Criteria for UCG

4.1 Introduction

UCG site selection depends upon a number of parameters related to coal, strata, water conditions and surface facilities. Most important parameters are coal rank, seam thickness and depth, type of overlying and underlying strata, permeability and porosity of coal and strata, geological features such as faults, joints, beddings and fracture networks, location of potable aquifers & their composition and closeness to surface infrastructure.

This chapter presents a scheme for both resource assessment and selection of potential UCG sites in central Appalachia, based on a detailed set of site selection parameters. A case problem approach is used to show how these different parameters can be applied to the available data to identify potential UCG sites. In addition, the concepts developed in this research can be used to delineate requirements and criteria for UCG site selection.

The Central Appalachian Basin encompasses approximately 10,000 square miles in southwestern Virginia, southern West Virginia and eastern Kentucky. It is the most mature and extensively mined coal-producing region in the United States. However, difficult mining conditions, stringent environmental regulations, strong competition from other coal producing regions and other energy sources and depletion of most accessible and low cost reserves, have contributed to declining coal production in central Appalachia. As a result, it is important to examine alternatives to traditional mining for the region, including opportunities offered by UCG. This technology has the potential to harness energy from deep, thin, low-grade and unminable coal seams, thus greatly enhancing the availability of exploitable coal reserves.

4.2 Background

UCG is a process involving burning of coal insitu and bringing up the product in the form of heated gases commonly known as syngas. The renewed interest in commercial development of UCG technology can be attributed to the following factors.

- stringent environment and safety regulations specific to coal mining
- instable and politically motivated increases in petroleum prices
- increasing negative public perception about coal mining
- rapidly increasing mining costs
- decrease in economically minable resources
- environmental and economic potential of UCG
- ability to recover energy from previously mined coal seams
- applicability of UCG on low heating value, deep and relatively thin coal seams, considered economically unminable through conventional mining methods
- lower capital cost due to elimination of coal mining, transportation and ash management facilities
- reduced surface footprint

In order to realize the full economic and environmental potential of UCG, proper site selection is a key factor [Sury, Kirton et al. 2004]. One of the major contributing factors in the failure of UCG pilots in Hoe Creek and Carbon County Wyoming, USA, was poor site selection [Clean Air Task Force 2009]. These projects resulted in the contamination of potable ground water and seriously hampered further developments of UCG in the U.S [Burton, Friedmann et al. 2006]. Although the U.S. DOE heavily funded the pilot researches in the 1970’s and 80’s, the resulting environmental impacts (resulting due to poor site selection and process control) blocked further funding into UCG. This emphasizes the importance of a well thought-out resource assessment plan for development of UCG sites.

4.3 Sıte Selectıon/Assessment Crıterıa

The literature on UCG indicates that pilot projects and trials have been conducted for several coal ranks, depths, seam conditions, geological and hydrological settings with different success levels. Over the last 100 years, experiments have been carried out on coals varying from lignite to anthracite, shallow depths to deep lying and horizontal to steeply dipping coal seams. From these studies, the following parameters are considered the most important for the selection of a proper UCG site:

- Coal Rank/Type
- Seam thickness
- Seam depth
- Seam inclination
- Seam structure
- Permeability and porosity
- Moisture contents
- Hydrogeology of the area and ground water issues

Other relevant parameters include:

- Quantity of resources
- Available infrastructure
- Presence of coalbed methane
- Land use restrictions and other regulatory requirements

In this chapter, the most relevant parameters for site selection have been reviewed and applied for selection of sites in the Appalachian region of the U.S. to analyze the potential for application of UCG.

4.3.1 Coal Rank

All types of coal ranging from lignite to anthracite can be gasified [Burton, Friedmann et al. 2006], as demonstrated successfully in surface gasifiers and tested for UCG. However, some type of coals are easier to gasify than others. For example swelling and coking coals can block the linkages between injection and production wells upon heating and can result in decreased permeability and porosity of coal [Couch 2009]. Testing on anthracite and semi-anthracite was conducted in Former Soviet Union and Bois-la-Dame Belgium [Thompson, Mann et al. 1976; Burton, Friedmann et al. 2006]; however, the results were not very encouraging.

Low rank coals especially lignite and sub-bituminous are preferable for UCG as the matrix tends to shrink on heating, resulting in enhanced permeability and improved linkages between injection and production wells [Bialecka 2009]. Low rank coals are preferred for gasification because they are at relatively shallower depth and easy to ignite and they do not form hard coke residue and are softer which makes it easy to develop a gasifier [Thompson, Mann et al. 1976]. The other reason for giving less preference to anthracite for UCG is its premium value. If anthracite for some reason is not minable through conventional mining methods, then it may be considered for gasification [Thompson, Mann et al. 1976]. Thus, the literature advocates that sub bituminous, non-coking coals are most suitable for gasification.

A study of coal rank trends by Hower and Rimmer shows that coal ranks generally increase towards the southeast in the Central Appalachian Basin in southern West Virginia, western Virginia, and eastern Kentucky but the ranks decrease towards the Alleghany front in Virginia and West Virginia [Hower and Rimmer 1991]. The study utilized volatile matter as an important parameter in ranking coals. The Pocahontas No.3 coal in southern West Virginia, is ranked as low volatile bituminous in McDowell and Wyoming counties. In central Buchanan County Virginia, the Pocahontas No.3 is ranked as low volatile bituminous, with volatile matter as low as 17% [Hower and Rimmer 1991]. However, the Burtons Ford coalbed to the south in Russell and Scott Counties, Virginia, has a high volatile A rank and coals above the Pocahontas No. 3 exhibit parallel trends, though at lower rank levels [Hower and Rimmer 1991].

Conrad et al. prepared a coal rank map for the Central Appalachian Basin based on percentage volatile matter which indicates the coal rank increases from high-volatile A bituminous (lower rank) in the northwest and west to semi-anthracite (high rank) in McDowell and Wyoming Counties, West Virginia [Conrad, Miller et al. 2006]. Overall, majority of coal in Central Appalachia ranks between sub-bituminous to bituminous with some smaller areas of semi-anthracite.

4.3.2 Seam Thickness

Coal seam thickness is another important site selection parameter. Initially there was a hope that UCG may effectively be applied to very thin coal seams that were not recoverable through conventional mining methods. However, it was found that UCG works best for thicker coal seams, especially seams more than one meter thick [Lauder and Smith 2012]. Although Russians tried to gasify coal seams less than one meter thick, the heating value of gas was very low for these seams [Burton, Friedmann et al. 2006]. The decrease in the heating value in thin seams may be attributed to the more pronounced heat losses to the strata and difficulty in controlling the shape of gasifier passages, which may become wide and allow the air to bypass reaction fronts and burn the forming syngas [Thompson, Mann et al. 1976].

Although Ergo Exergy states that coal seams as thin as 0.5 m may be gasified through UCG [Shafirovich and Varma 2009], a coal seam thickness of more than 2.0 m is preferable. Thicker coal seams (> 2m) require fewer boreholes to gasify more amount of coal, providing both economic and environmental advantages [Sury, Kirton et al. 2004]. In thinner seams the inert floors and roofs act as heat sinks whereas in thick seams the channel is in the same cross sectional area and the entire surface area is reactive, thus there is no heat sink and all heat flows react on coal. Moreover the thick coal seam prolongs the working life of gasifier [Thompson, Mann et al. 1976]. The lower limit for the seam thickness should be more than 2 m, with the ideal thickness around 5 m to 10 m. This ideal thickness provides significant quantities of coal to be gasified without involving unacceptable ground movements and subsidence [Couch 2009]. The upper limit for coal thickness is usually dependent upon geomechanical properties of the surrounding strata and potential of cavity collapse. Russian projects indicate no maximum limit to seam thickness [Burton, Friedmann et al. 2006], but with a seam thicker than 20 m, there is a greater risk of subsidence and cavity collapse [Couch 2009]. Thus, most suitable seams may lie between a thickness of 2m and 20 m.

The Central Appalachian Basin consists of coal seams that are comprised of widely distributed multiple coalbeds. These coal seams from oldest to youngest are; the

Pocahontas No. 3, Pocahontas No. 4, Fire Creek/Lower Horsepen, Beckley/War Creek, Sewell/Lower Seaboard, and Iager/Jawbone [EPA. 2004]. The Pocahontas coal seams include the Squire Jim and Nos. 1 to 7 with Nos. 3 and 4 the thickest and most areally extensive [EPA. 2004].

Appalachian coal seams are geologically and technically challenging because numerous thin seams (less than 1 m) are distributed throughout thick stratigraphic sections [SECARB. 2011]. Marshall Miller and Associates Inc. (MM&A) has developed various coal isopach maps for different fields of the Central Appalachian Basin targeting the Lee and Pocahontas formations. A net coal isopach for the Frying Pan field, Virginia representing composite coal thickness of the Lee and Pocahontas formations (Greasy Creek to Pocahontas No. 1 coal seams) indicates a net coal thickness of 6.9 m (22.5 feet) [SECARB. 2011]. The average net coal thickness for the Sourwood field, Virginia in the Lee and Pocahontas formations is about 8.0 m (26.4 feet), whereas the average net coal thickness in the Lick Creek field, Virginia for the same formations is 5.7 m (18.6 feet) and for the South Oakwood filed, Virginia it is 7.4 m (24.4 feet) [SECARB. 2011]. The Beckley seam in the Loup Creek field, West Virginia has an average thickness of 1.6 m (5.3 feet); however, it ranges from 0.5 to 2.9 m at places [SECARB. 2011]. Figure 4.1, Figure 4.2, Figure 4.3 and Figure 4.4 show the net coal isopach for different fields in the Basin, adapted after SECARB 2011.

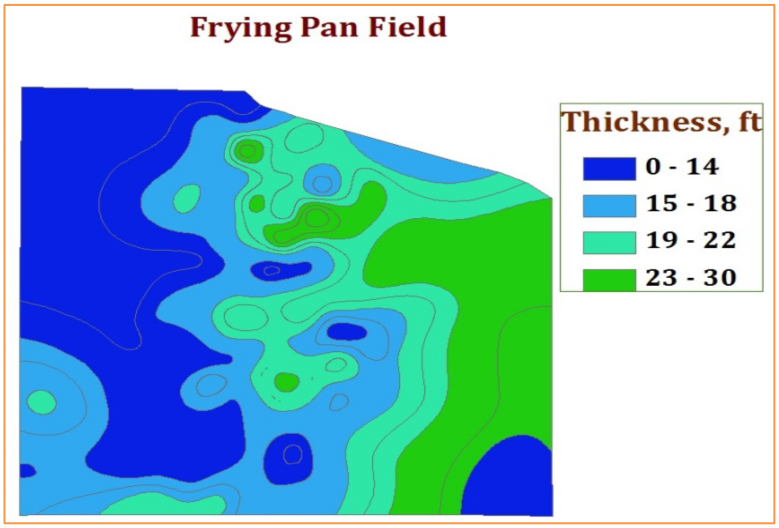


Figure 4.1: Net coal isopach for Frying Pan field, VA

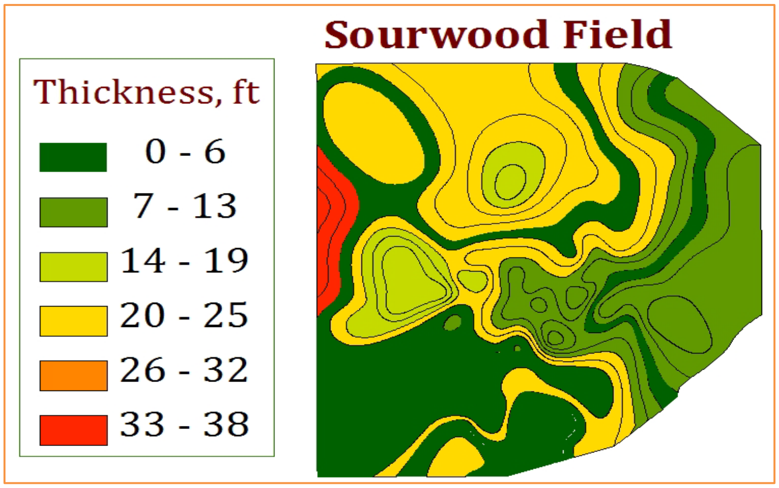


Figure 4.2: Net coal isopach for Sourwood field, VA

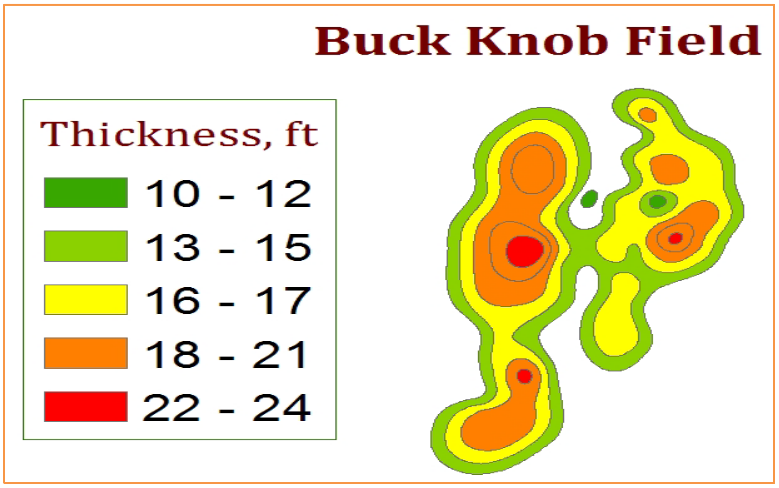


Figure 4.3: Net coal isopach for Buck Knob field

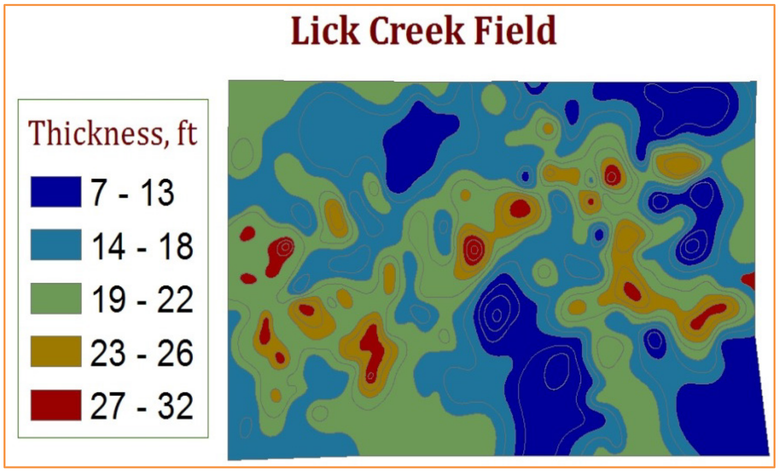


Figure 4.4: Net coal isopach for Lick Creek field

Figure 4.5 shows a net coal thickness isopach adopted from Ripepi indicating a net coal thickness varying from less than one meter to more than 10 m [Ripepi 2009]. However, this is the composite thickness of various coal seams in the region especially in the Lee and Pocahontas formation. The individual seams in this region are generally thin (< 1 m) with some thicker seams ranging to more than 2 m in thickness.

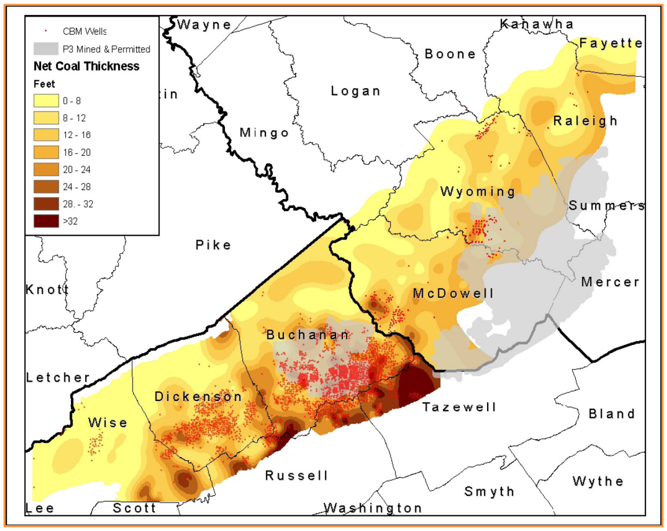


Figure 4.5: Net coal thickness isopach for Central Appalachia

Any typical cross section of the area indicating thickness of different coal members will show that there are multiple coal seams in the region with varying depths and thickness. The composite thickness of these seams reaches up to more than 10 m (~ 30 ft.) in some areas, however, individual seams are generally thin but some are thicker than one meter and can be potential UCG sites. A study is needed to see the applicability of UCG on multiple seams in the region especially the ones that are relatively closer to each other. Figure 4.6 suggests a schematic of this idea.

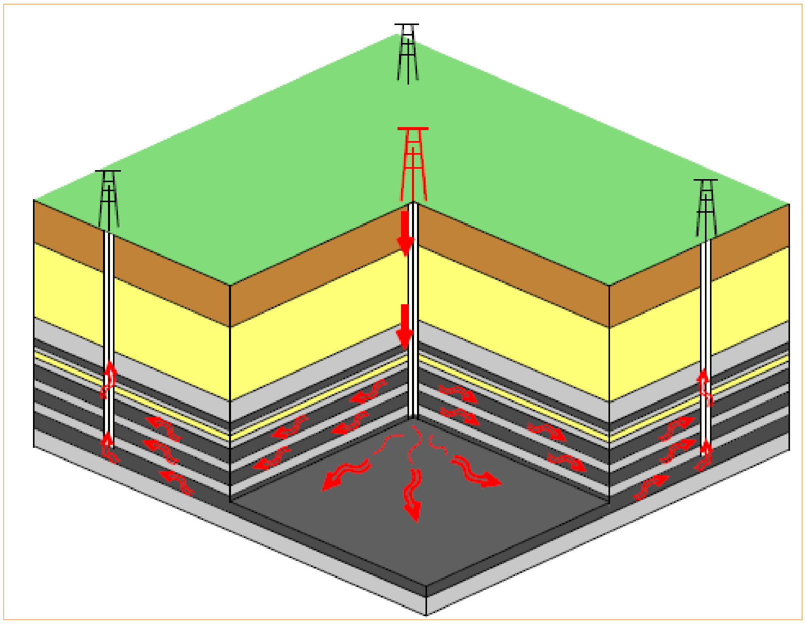


Figure 4.6: UCG application on multiple seams

4.3.3 Depth of Coal Seam

UCG trials have been conducted at varying depths; for example in the Russian and the U.S. experiments varied from 30 m to 350 m deep, whereas in Europe, trials at much deeper depth (600-1200m) were carried out [Shafirovich and Varma 2009]. However, the practical depth at which UCG can be applied effectively is a function of hydrostatic pressure in the reactor cavity, potential for subsidence and depth of potable aquifers in the region. Burton et al. recommend 12 m as minimum required depth of coal seam with preference for coal seams deeper than 150 m for better control of UCG operations [Burton, Friedmann et al. 2006].

In the shallower seams, the risk of gas leakage and likelihood of intersecting potable aquifers increases. The burn cavity at shallower depths gives rise to potential for collapse and subsidence. However, decreased hydrostatic pressure at shallower depths ensures water inflow into the cavity thus reducing the chances of water contamination by outflow of contaminants under increased cavity pressures. However, the cavity pressure control at shallow depths is essential because even a transient increase in burn cavity pressure will force gas leakage due to minimal hydrostatic pressure [Couch 2009] .

On the other hand, deeper coal seams solve the problem of contaminating potable aquifers, as most of the aquifers at this depth are already saline and not classified as potable [Couch 2009]. Secondly, due to increased hydrostatic pressure, maintaining a steady condition between strata and burn cavity pressures is relatively easy. This gives increased process control. However, the increased pressure at greater depths tends to decrease the permeability of the coal and the linkage between injection and production wells is difficult [Sury, Kirton et al. 2004].

Drilling at greater depths may increase operating costs but recent developments in drilling technology have made it possible to operate at greater depths without facing technical and operational difficulties. New technologies and design solutions have promoted development of deep coal seams, increased control over rock pressures, reduction in the well requirements thus decreasing the drilling costs and application of UCG on abandoned mines [Zorya, JSC Gazprom et al. 2009]. In addition to increase in hydrostatic pressures and geo-mechanical stresses, the temperature also increases at greater depths, but this increase has no known severe impacts on UCG operations.

The depth of different coal seams in central Appalachian region ranges from outcrops to more than 800 m. The Pocahontas No. 3 coal seam ranges in depth from outcrop along the northeastern edge of the basin to about 762 m and the depth of Pocahontas No. 4 is similar to that of No. 3 with No. 4 overlying No. 3 seam roughly 9 to 30 m (30 to 100 ft.) [EPA. 2004]. The Fire Creek/Lower Horsepen varies in depth from152 m (500 ft.) to a maximum of 457 m (1,500 ft.) whereas the Beckley/War Creek coalbed reaches to a maximum depth of 610 m (2,000 ft.). The Sewell/Lower Seaboard coalbed is fairly shallow with less than 150 m (~500 ft.) over almost half of its area and the depth of Iaeger/Jawbone Coal Seam is similarly less than 150 m (~500 ft.)[EPA. 2004].

4.3.4 Seam İnclination

Seam inclination or dip is not a restraining factor for UCG site selection criteria [Shafirovich and Varma 2009]. In Russian and some U.S. trials, steeply dipping seams (> 50°) were used successfully for UCG. UCG is preferable for exploiting steeply dipping coal seams because these seams are usually considered less economical and technically difficult for conventional mining techniques than horizontal seams [Lamb 1977]. Secondly, the process to gasify steeply dipping coal seam is relatively simple, easier and economically more attractive than mining the coal [Lamb 1977]. The drilling requirements for steeply dipping seams are less than those for horizontal beds [Bialecka 2009].

Burton et al. and Sury et al. prefer shallow dipping seams to steeply dipping seams because of difficulties in process controls and associated difficulties such as chimney formations and damage to the down dip production well as a result of strata movements [Sury, Kirton et al. 2004; Burton, Friedmann et al. 2006].

The regional dip of coal bearing strata in the Central Appalachian Basin is to the northwest at a rate of 75 ft. per mile. Generally, the dip of coal seams in Pocahontas and Lee formation are gentle, usually ranging from 1.2 ft. per 1000 ft. to 1.4 ft. per 1000 ft. [SECARB. 2007].

4.3.5 <u>Seam Structure</u>

A hard rock overlaying a coal seam may decrease the risk of subsidence and caving though it may pose problems in drilling of wells. An impermeable rock covering may provide a shield preventing gas losses but it may limit the water supply [Couch 2009]. The presence of joints, faults cleats and slips present in the target seam or other seams and confining strata may provide potential gas leakage paths [Sury, Kirton et al. 2004]. Similarly permeable rock matrices, mining/caving induced features, fissures and abandoned borehole may provide path for fluid inflow and outflow [Sury, Kirton et al. 2004] and can result in cavity flooding or ground water pollution.

Similarly, if there is a series of seams at different depths in the area, then it is important to classify them according to their potential to be mined, gasified or methane extraction. The sequencing in the use of different technologies is very important in this case [Couch 2009]. If the topmost seam is mined first, then usually the lower seams are undisturbed and can be used for future exploitation, however, it is very common that only few of the seams are economically minable [Couch 2009]. The mining of lower seams first may result in strata relaxation, resulting in the production and /or expansion of existing fissures and cracks, thus providing fluid flow paths.

The major formations in the Central Appalachian Basin are the Pocahontas, New River/Lee and Kanawha/Norton. The Pocahontas formation consists of massively bedded, medium grained subgraywacke, which can be locally conglomerated [EPA. 2004]. Gray siltstones and shales are interbedded with sand stone and coal seams usually make up about two percent of formation thickness. The New River/Lee formation overlies the Pocahontas formation conformably in northeastern portions but have an unconformity in the east central portion [EPA. 2004]. The coalbeds in this formation thins and pinches out towards the south and west. The Kanawha/Norton formation is composed of irregular, thin to massively-bedded subgraywackes interbedded with shale and contains over 40 multi-bedded coalbeds. The Central Appalachian Basin is characterized structurally by broad, open, northeast-southwest trending folds that typically dip less than five degrees and faults and folds associated with this 25 mile-wide and 125 mile-long structural feature are more intense, as evidenced by overturned beds and brecciated zones in some locations. Two dominant joint patterns run within the coals [EPA. 2004].

4.3.6 Permeability and Porosity

Permeability of coal plays an important role in the linking of injection and production wells. High rank coals and deep seated seams generally have low permeability [Couch 2009] and exhibit difficulty in flow path linkages. Permeability also effects the burn cavity width & gasifier growth and the approach of low permeability zone at production well indicates the possible end of gasifier life [Creedy, Garner et al. 2001].

Ghose and Paul prefer the development of in seam channels for gasification over long distances and in their opinion the natural permeability of coal seams is not sufficient to move the gases to and from the reaction zones [Ghose and Paul 2007]. Ray et al. propose use of hydraulic fracturing to enhance the natural permeability of coal [Ray, Panigrahi et al. 2010].

The permeability of overlying strata is an important consideration. The permeable rocks will allow water to inflow into the cavity; they will also allow reaction products to flow into the strata and can result in pollution or contaminant movement at some distance from the reaction zone [Creedy, Garner et al. 2001]. However, Sury et al. suggest that due to short lived gas escapes, the effect of rock matrix permeability of adjacent strata on the gas leakage is not important except where there are large joints or fissures or very high matrix permeability [Sury, Kirton et al. 2004].

For the Central Appalachian Basin, Hunt and Steels suggest a minimum permeability of 0.1 to 0.5 md with the Pocahontas No. 3 coalbed having a high average permeability of 5 to 27 md [Lyons 2003]. Hunt and Steels also state that coalbeds in Appalachian Basin are underpressured due to geological history, extensive coal mining and many oil and gas wells in the vicinity [Lyons 2003]. As per Mr. Tony Scales (Virginia Department of Mines, Minerals and Energy), the most permeable layers in the geologic subsurface of Virginia are coal seams [EPA. 2004]. SECARB reports suggest the following average permeability values for different fields in the region: Frying Pan field-11md; Sourwood field-10 md; Lick creek Field 7.5 md; Buck Knob 10 md and South Oakwood field 7.5 md [SECARB. 2011]. As coalbed methane production matures in these fields over tens of years, the permeability of the coal will increase.

4.3.7 Moisture Contents

The amount of water present in the seam affects the UCG process in two ways; firstly, an excessive amount of water makes the ignition of seams difficult and inrushes of water through fissures, faults and joints occasionally putout/quench the fire. On the other hand, presence of a certain amount of water is helpful once the reaction is started, as it helps in the water gas reaction [Thompson, Mann et al. 1976]. In the reduction zone of the gasification channel, major reaction takes place when $H_2O_{(g)}$ and CO_2 react with an incandescent coal seam and reduce to H_2 and CO under high temperature[Yang, Zhang et al. 2008].

$$C + CO_2 \longrightarrow 2CO \qquad -162.4\ \text{MJ/kmol}$$

$$C + H_2O_{(g)} \longrightarrow CO + H_2 \qquad -131.5\ \text{MJ/kmol}$$

Thus, the presence of water is beneficial to the reaction and it can increase the amount of hydrogen in syngas composition. Secondly, the presence of water in the seam acts as an efficient gas seal [Thompson, Mann et al. 1976], helping in the reduction of reaction gases and contaminants escape out of the burn cavity.

4.3.8 Hydrogeology and Ground Water issues

The problems at Hoe Creek and in Williams county Wyoming, USA have highlighted the importance of site characterization especially in relation to the presence of groundwater resources. These trials not only contaminated local potable aquifer, they created a great hindrance to future UCG research in the U.S. Primarily, the DOE sponsored these projects and the migration of organic compounds (e.g., benzene, toluene, ethyl benzene, and xylene) contaminated a coal seam aquifer located at a depth of about 55 m below the surface [Burton, Friedmann et al. 2006].

The knowledge gained from the trials at Hoe Creek is valuable and suggests that downgraded consideration should be given to UCG sites that are surrounded by potable aquifers. The second important lesson is to maintain the cavity pressures at a level lower than hydrostatic pressures in order to prompt controlled inrush of water into the cavity and to avoid outflow of contaminations or reaction gases from the cavity. This requires maintaining the hydrostatic gradient towards the cavity areas by pumping water from the cavities to facilitate groundwater inflow towards the gasifier chamber. [Sury, White et al. 2004]

Hydrogeological mapping of the area is very important to avoid such incidents and it should include detailed information about lithology, fractures (faults, joints, fissures etc.), folds and aquifer extent & thickness [Creedy, Garner et al. 2001].

The potable water resources in Central Appalachian region are usually at shallow depths; deeper aquifers are mostly saline. As reported by EPA, water wells are typically 75 to 100 feet deep in the Pennsylvanian aquifer located in the Kentucky portion of the basin and produce one to five gallons per minute of water. In the Virginia region, the primary aquifer is the Appalachian Plateau Aquifer, which has wells typically 50 to 200 feet deep and produce one to 50 gallons of water per minute [EPA. 2004]. In the West Virginia region, the primary aquifer is the Lower Pennsylvanian aquifer with wells commonly 50 to 300 feet deep and produce one to 100 gallons per minute [EPA. 2004]. Produced water volumes from coal seams in the basin are relatively small, typically several barrels or less per day per well, with total dissolved solids (TDS) greater than 30,000 milligrams per liter (mg/L). In Virginia, the depth to the base of fresh water is approximately 300 feet and in West Virginia it is estimated to be between 280 to 730 feet [EPA. 2004]. Thus, deep coal seams will typically avoid the potable aquifer and may not pose threats to drinking water supplies.

4.3.9 Quantity of Resources

Quantity of resources is an economic and profitability criterion that is essential for funding decisions. Three types of resources can be considered for UCG development, developed or reserve deposits, undeveloped or prospective deposits and deposits in abandoned or ceased coal mines [Bialecka 2009]. For commercial development of UCG, a resource of sufficient quantity is required to offset expenses and ensure profitability and long economic life of the project. Generally, the utilization of syngas determines how much quantity of coal is required for specific project needs. For example to feed smaller power generation units serving local needs, a smaller resource may be sufficient, on the other hand, larger industrial units like chemical plants require large amounts of coal. Shafirovich et al. state that to feed a 300 MW UCG-based combined cycle power plant with an efficiency of 50% and running for 20 years, 75.6x109 Nm^3 of syngas with a heating value of 5.0 MJ/m^3 is required. This requires gasification of a coal deposit of about 33x10^6 metric tons [Shafirovich, Varma et al. 2009].

The Central Appalachian region has produced more than 17 billion tons of coal with the peak production in the 1990's at approximately 275 million tons/year, which dropped to almost 240 million tons/year since then [Mark 2006]. The recoverable reserves estimated by EIA on sulfur content basis are approximately 27,000 million tons [Milici and Dennen 2009]. This has been one of the most productive coalfields of the USA and there are sufficient reserves of unminable coal for development of large-scale UCG operations.

4.3.10 Availability of İnfrastructure

Another major aspect for site selection is the presence of available infrastructures including roads, electricity, utility lines and gas transmission lines. An ideal location is one that is close to a major transportation/roads network, has existing gas pipelines in close vicinity and the land available for commercial/industrial units or power plants that feed upon product gases.

The Central Appalachian Basin is one of the most productive and mature coalfield in the U.S. It is a center of coal and coalbed methane production and numerous mines, and CBM production wells are located throughout the region. Due to maturity of the region, infrastructure is available in this area.

4.3.11 Presence of Coalbed Methane

Although effects of the presence of coalbed methane on UCG are not yet extensively known and very little literature is available in this regard, the general idea is that if methane is not in a commercially recoverable quantity in the seam, its presence may enhance heating value of product gas and may aid the burning process. However, if commercially recoverable quantities of coalbed methane are present , then there is dispute in the sequence of energy recovery from coal seams [Couch 2009]. The in-seam drilling techniques established to facilitate methane recovery can be helpful in UCG applications but is very important to avoid extracting CBM in such a way that subsequent application of UCG becomes practically impossible [Couch 2009]. Although coalbed methane is a more mature technology especially in Australia and US, it recovers much less energy [Couch 2009]. As stated by Carbon Energy UCG recovers more than 20 times the energy recovered by coalbed methane drainage methods [Meany and Maynard 2009]. However, further research is needed to establish the synergies between UCG and coalbed methane.

The Central Appalachian Basin is one of the most important CBM fields in the U.S. Production of CBM started in 1988 in the Nora Field in Dickenson County, Virginia, which is the most productive field, followed by the Oakwood Field in Buchanan County, Virginia. Since then more than 4600 wells have been drilled in southwest Virginia [Ripepi 2009]. At the end of 2006, estimated production from Central Appalachian Basin was about 777 Bcf with Virginia producing 90% of CBM production [Ripepi 2009]. These production wells are usually hydraulically fractured to enhance CBM recovery; the typical fracture ranges in length from 300 to 600 feet from the well in either direction, but can extend from 150 feet to 1500 feet with fracture widths ranging from one eighths inch to almost one and a half inch [EPA. 2004]. Thus, a thorough research study is needed to establish the synergies between CBM production development and subsequent application of UCG.

4.4 Chapter Conclusions

Table 4.1 shows parameters in the order of their importance for a proper UCG site selection.

Table 4.1: Site Selection Criteria

Parameter	Requirement
Seam thickness	Preferably >1 m, ideally 5 -10 m
Seam depth	> 150 m, ideally > 200 m
Coal rank / type	Sub bituminous or lower rank, ideally non coking, non-swelling coals
Seam dip / inclination	Any but steeper is preferred as it may be technically difficult to mine through conventional methods
Moisture contents	Controlled inflow of water or high moisture contents are desirable especially after initiation of burning
Groundwater	Avoid potable aquifer and large water bodies
Permeability and Porosity	More permeable the seam is, easy to link the injection and production well, more permeable the strata is more chance of gas leakage and contaminant movement
Seam/strata structure	Avoid excessively fractured, faulted and broken rocks as they may cause water inrush or product gas and contaminant leakage
Coal quantity	Dependent upon gas utilization and profitability
Infrastructure availability	Roads, electricity and power transmission lines
Presence of CBM	Depends upon economics or commercial value of CBM deposit and its interoperability with UCG

The Central Appalachian Basin is composed of several coal seams ranging in thickness from less than one meter to about two to three meters at places. These coal seams are at a varying depth of a few meters to more than 800 m. The average seam inclination is normally flat rather than steep. Potable aquifers are found at a depth varying from 25 m to more than 100 m at some places, but overall drinking water is at shallower depths. Rank of coal is generally bituminous in appreciable quantity, making the basin a potential site for UCG targeting any major thick seam or composite of seams with average thickness of more than 2 m.

This basin has had significant production of CBM with more wells being drilled regularly. The coal seams and strata have been subjected to hydro fracturing to enhance CBM recovery. This infrastructure and network of wells can be an important economic benefit for UCG if they can be utilized as injection and/or production wells for gasification. The increased fractures can be helpful in linking the injection and production wells but can also pose problems of cavity control and contaminant migration. This research gap advocates a strong need for a research study to establish the synergy between CBM and UCG operations in the basin.

Chapter 5 - GIS Model for Selection of Suitable Sites for UCG

5.1 Introduction

Proper site selection is one of the most important parameters in the success or failure of (UCG) projects. A properly selected site helps in realizing the full environmental and economic potential of this technology [Sury, Kirton et al. 2004], whereas a poor site selection may result in the failure or serious environmental consequences for the project. This is evident from the pilots in the Hoe Creek and Carbon County, Wyoming, where poor site selection is attributed as one of the major factors resulting in the contamination of potable groundwater resources and nearby aquifers [Clean Air Task Force 2009]. This highlights the significance of the site selection stage for the UCG project.

This chapter describes the development of a GIS model that assists in the selection of suitable sites for UCG based on the criteria listed in the previous chapter. The model uses powerful features of two GIS software: ESRI's ArcGIS [ESRI. 2012] and Clark Labs' IDRISI [Clark Labs 2012] and develops a general process flow chart applicable to any site. In this chapter, all the steps involved in the development and use of this model are explained in detail. The model is applied to the Frying Pan, Sourwood, Lick Creek and South Oakwood fields in Virginia; however, this model is not site specific and can be applied to any site provided the input data is available for that site. This chapter also describes the data required for this model, different data sources, preparation of data in the required formats and creation of data layers for use in the software.

5.2 Data Required

This model uses the site selection criteria established in the previous chapter and most of the data required for the model is based on that criteria. However, the model is flexible enough to let the users utilize data that is not part of those criteria provided it is in the right format. For example, cost of lands, labor availability, regional population, vicinity of schools, colleges, recreational activities and hospitals, other utilities and climatic data of the area can also be incorporated in the model. However, this data needs to be in the suitable format, properly prepared, projected to suitable scale, standardized, factor weighted and displayed in the form of data layers for use in the software.

For this demonstration model, the following data in the format of data layers for use in ArcGIS and IDRISI was used.

- Coal rank
- Seam thickness
- Seam depth
- Seam inclination/dip
- Permeability
- Hydrology of the area
- Coalbed methane presence and gas contents
- Coal quality data
    - Moisture content
    - Ash
    - Sulfur
    - Carbon content
    - Volatile matter
    - BTU per pound
- Infrastructure availability
    - Primary Roads
    - Rail Roads
- Land use restrictions and other regulatory requirements
    - Forests
    - Agricultural land
    - Highly developed/residential areas

5.3 Data Format

For use in the GIS, initial data was mostly in the vector formatted shapefiles of polygons, lines or points. For example, the boundaries of coalfields were polygon shape files. The forests, coal isopachs and coal quality parameters were also vector data in the form of shapefiles. The coal quality data was added as attributes to the attribute table of field boundaries shapefile. It was later displayed as data layers in ArcGIS and IDRISI. The roads, railway lines, power lines and streams were lines shapefiles whereas elevation and land cover were raster dataset. The data imported to ArcGIS was in the shapefiles whereas the data layers for modeling in IDRISI were in the raster format because raster datasets are more easily configured in IDRISI.

5.4 Data Sources

Various sources provide vector data in the form of shapefiles for roads, forests, boundaries, water features, addresses, counties, political boundaries and demographic data. The U.S. census bureau provides boundaries, roads and water features in the form of Tiger shapefiles [U.S. Census Bureau 2012]. The demographic and census data is available from American FactFinder, a website managed by the U.S. Census Bureau [American FactFinder 2012]. The data relating to railroads network is available from Center for Transportation Analysis's (CTA) transportation networks website. CTA provides data for the North American railroad system in the form of downloadable shapefiles [CTA. 2011]. However, for a specific site, the rail network in the area has to be extracted after displaying in the appropriate software. The United States Geological Survey (USGS) provides topographic, elevation, land cover and water resources data [USGS 2011] . The data is available in the shapefiles, GeoTiff and GeoPdf format. The data can be downloaded for specific areas using interactive tools of "The National Map Viewer" in the required format [USGS 2012].

The data related to coal rank, seam thickness, seam dip, coal quality (ash, moisture, sulfur, carbon contents etc.) is generally site specific, and in most cases, the companies interested in the gasification acquire or generate this data internally.

5.5 Data Reliability

The data reliability depends upon the source from where the data is extracted. The data from the USGS websites and TIGER data is generally very accurate; however, the data available from private vendors, data clearinghouse websites and generally available online data has varying levels of accuracy. The data generated by the companies for their own use is typically more accurate than the data disseminated on the web based databases.

For the particular area used in the model, the data was collected from several sources including federal and state database providers like USGS, Census Bureau, TIGER database and various online databases, therefore the accuracy of some of the data was not very high. Secondly, the coal quality data was taken from a study of this basin conducted by SECARB to determine the potential of carbon sequestration in this area [SECARB. 2011]. Coal quality and individual seam data was available only for a few boreholes in the area and was extrapolated for the rest of the area, therefore the coal quality, seam thickness, seam depths and dip data is accurate for those boreholes only and is not a representative of entire study area. The data for the entire study area was extrapolated from this available data. The purpose of this data generation was to demonstrate its use in the model and to describe the processes through which data can be extracted and used for modeling. Focus was demonstration of this decision model not the accuracy of the data, therefore the results are not wholly representative of this area and are not intended for commercial application in UCG projects. The more accurate site-specific data can be generated based on the procedures described in this model that will provide highly accurate and dependable results for the specific sites

5.6 Data Preparation

The data imported into ArcGIS was in the format of vector shapefiles and was in varying coordinate systems. The data was projected to North American Datum 1927, State Plane coordinate system for Virginia South in Lambert conformal conic projection, to maintain the consistency of data and visibility of layers. Roads, forest and railway lines data was available for the entire state or larger parts of states than required for our study area and needed to be “clipped” to the study area. Coal quality data and other coal related parameters were in the form of a table and added to the ArcGIS as attributes of the area.

As distance from roads, forest and other infrastructure is more important than the physical presence of these structures in the area, the distance images for these features were created using the “Distance” command of IDRISI, after exporting the layers to IDRISI. The distance image is a Euclidean crow flight distance between each cell and the nearest of a set of target features and is more appropriate for analysis, as ranking on the basis of distance from features is more meaningful in spatial analysis for sites.

5.7 Data Layers

The following data layers (Figures 5.1- 5.14) were created in ArcGIS, after importing from different databases, projecting and adding attributes. These layers constituted the base data for further analysis and use in the modeling part. Coal rank, seam depth, coal seam thickness and coal quality data was taken from the SECARB study and extrapolated to the study area [SECARB. 2011]. Permeability and dip data was based on the average trend of the basin.

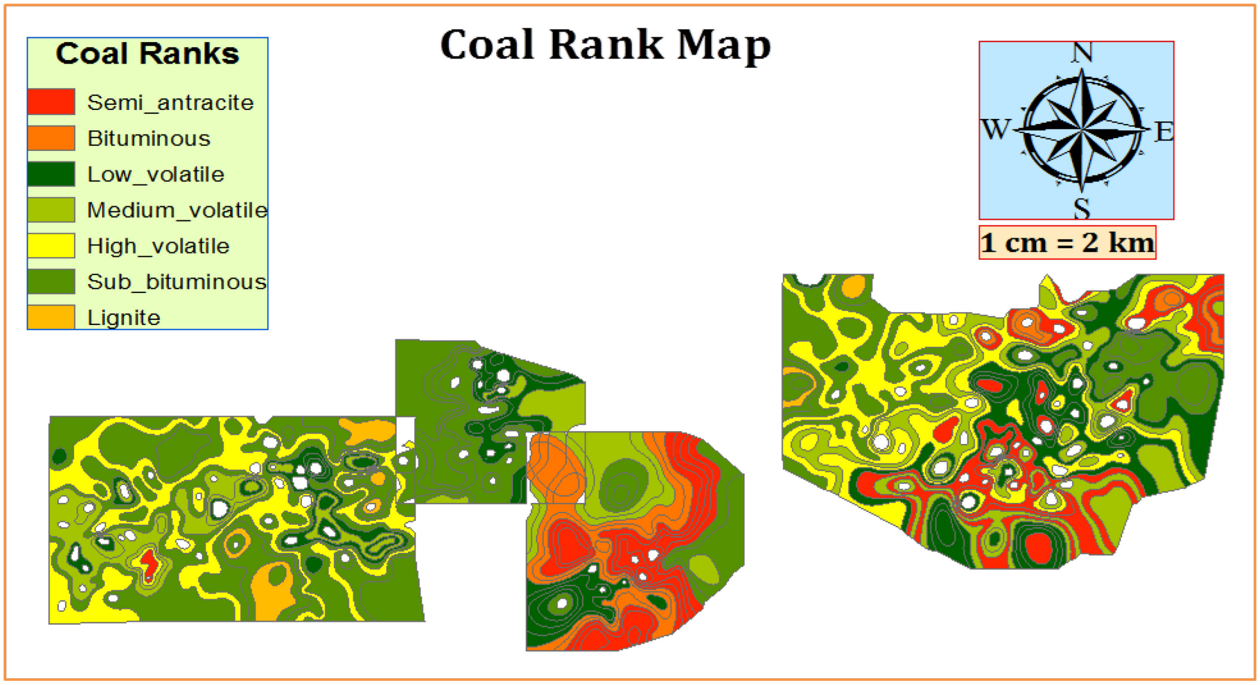


Figure 5.1: Coal rank layer for the study area

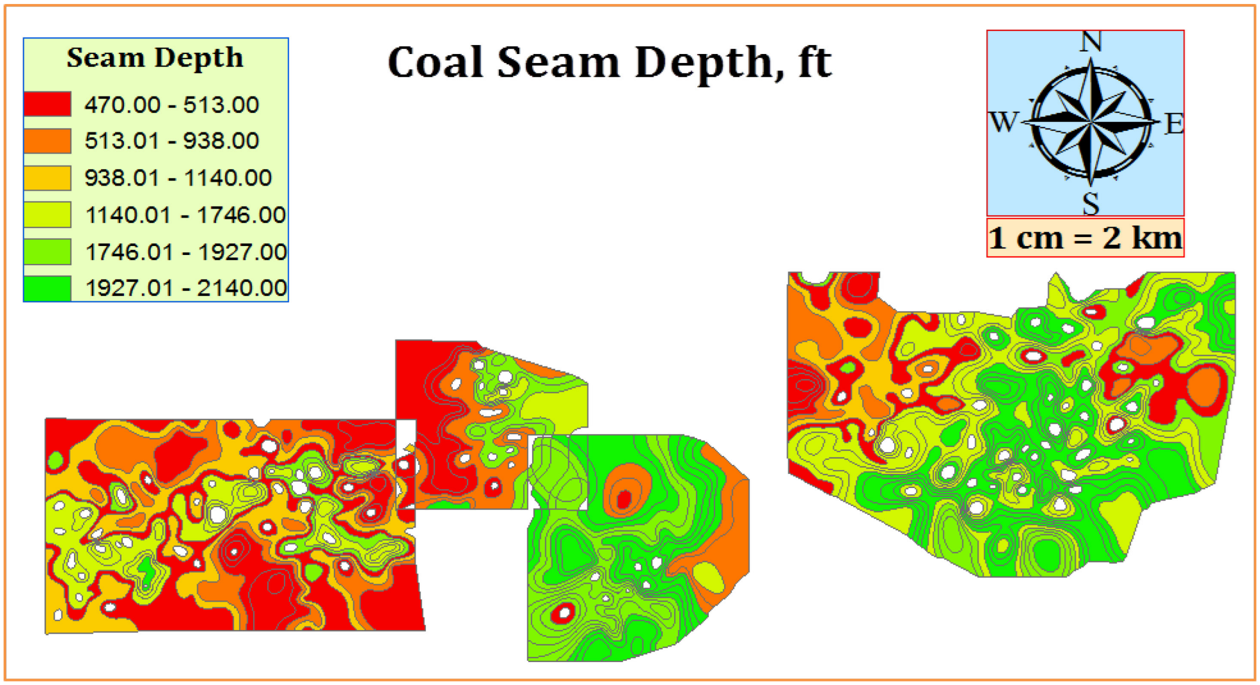


Figure 5.2: Coal seam depth layer

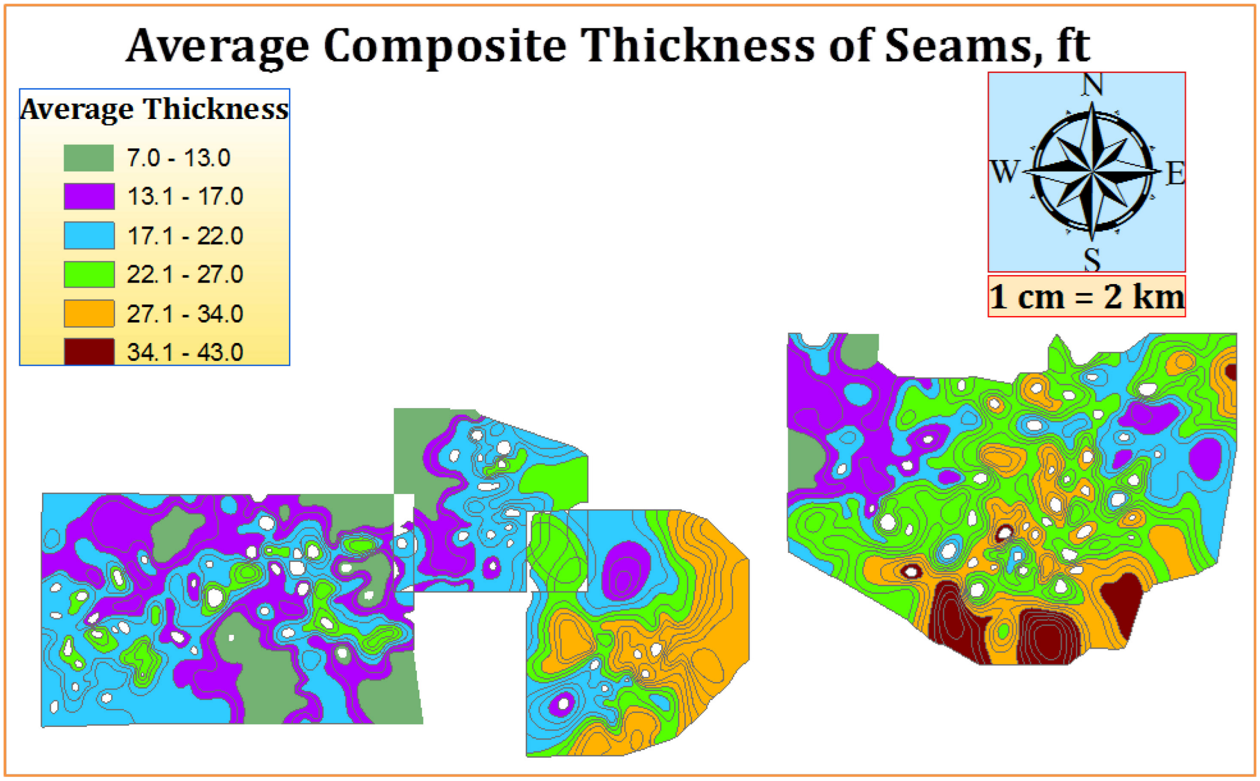


Figure 5.3: Data layer showing composite average thickness of seams

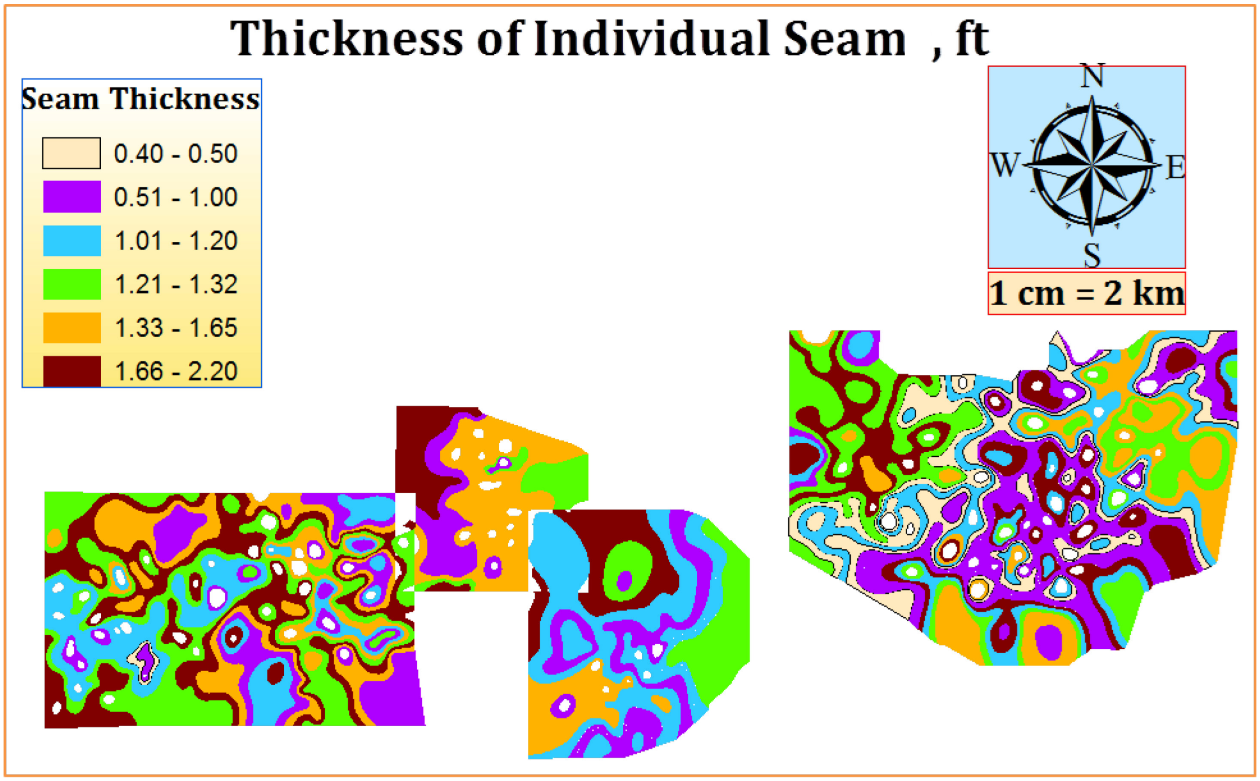


Figure 5.4: Data layer showing thickness of individual seam in the area

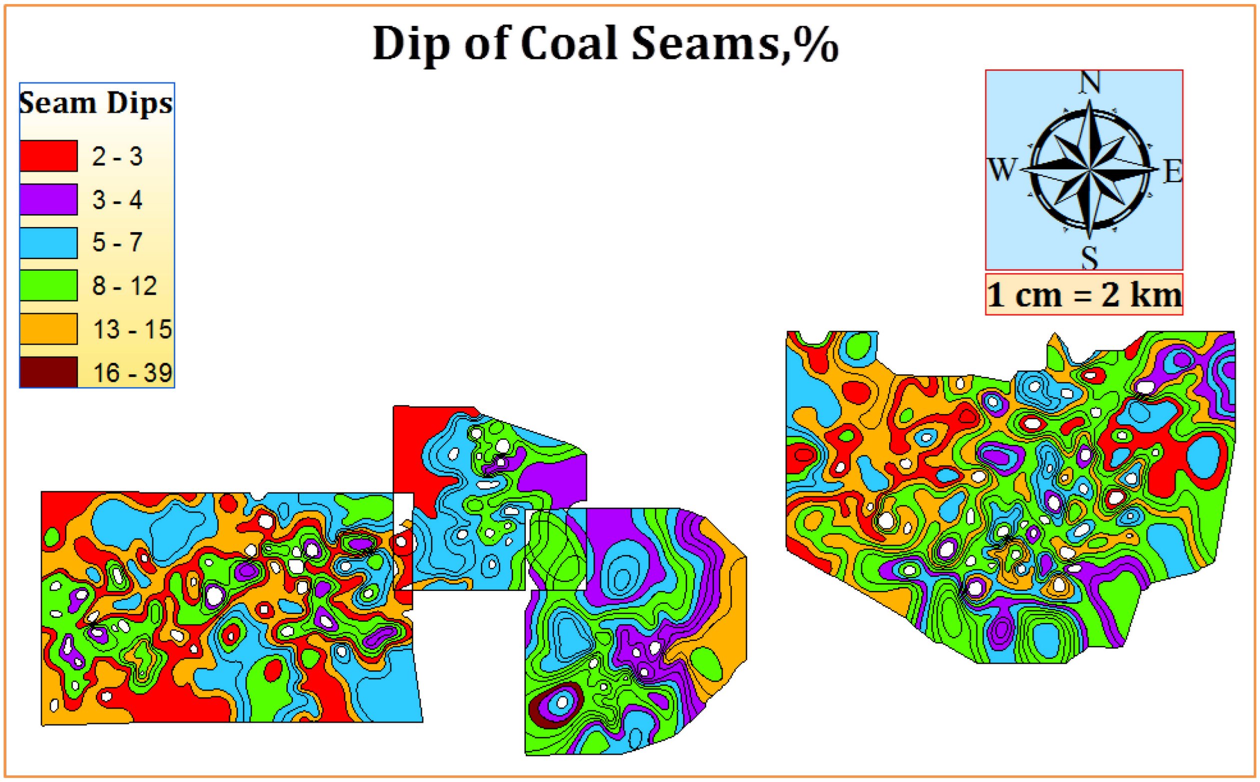


Figure 5.5: Coal seam dip, %

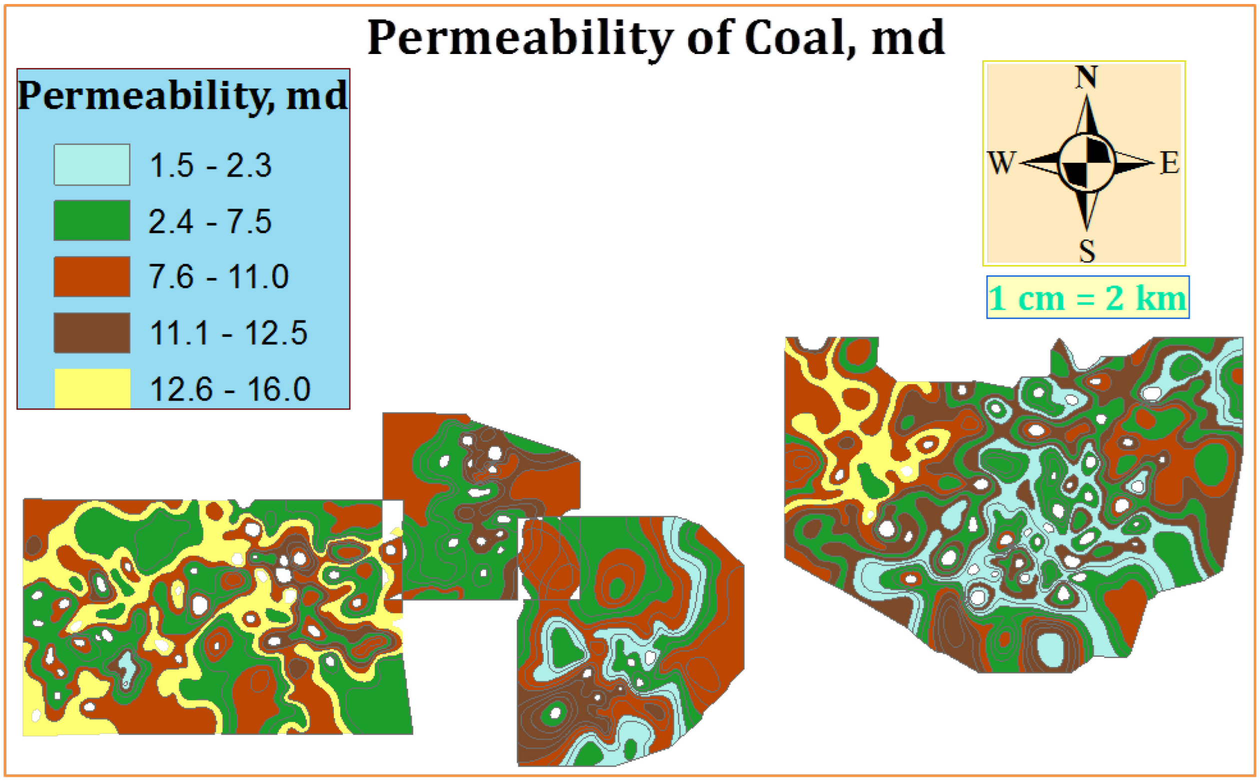


Figure 5.6: Permeability of coal, %

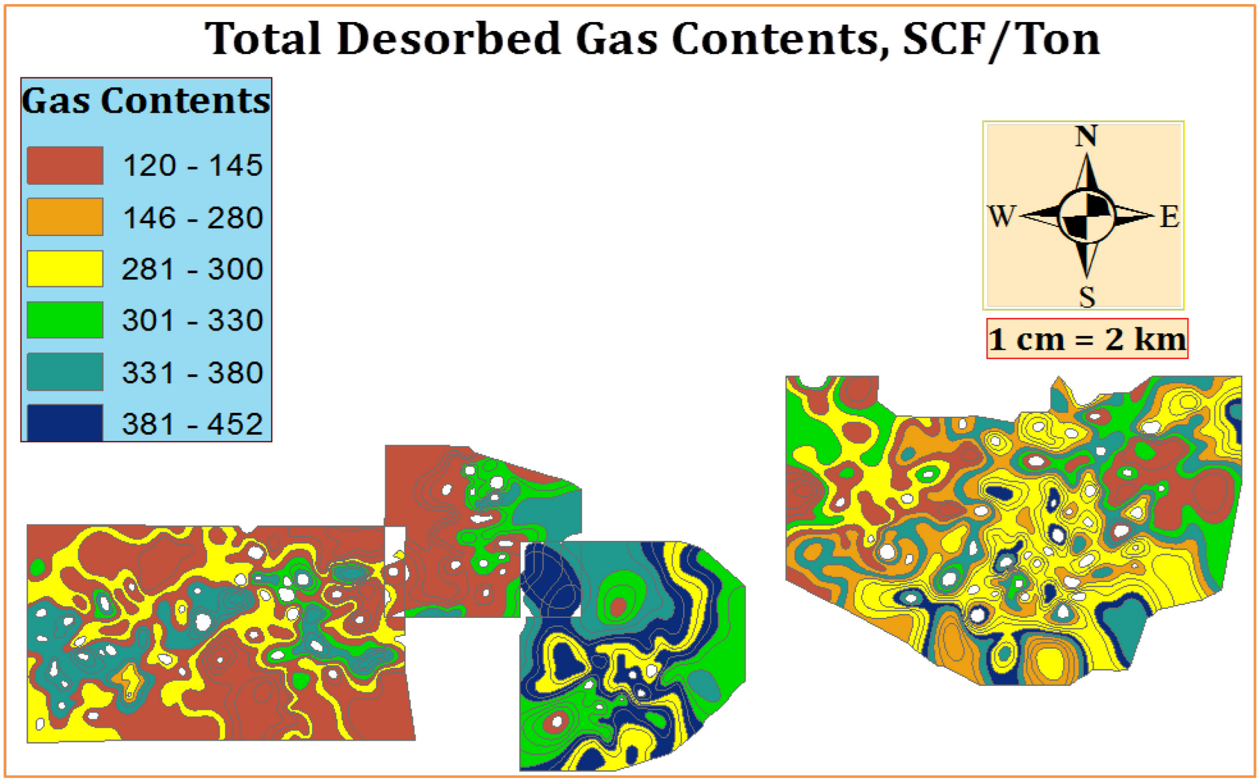


Figure 5.7: Total desorbed gas content, SCF/ton, as received basis

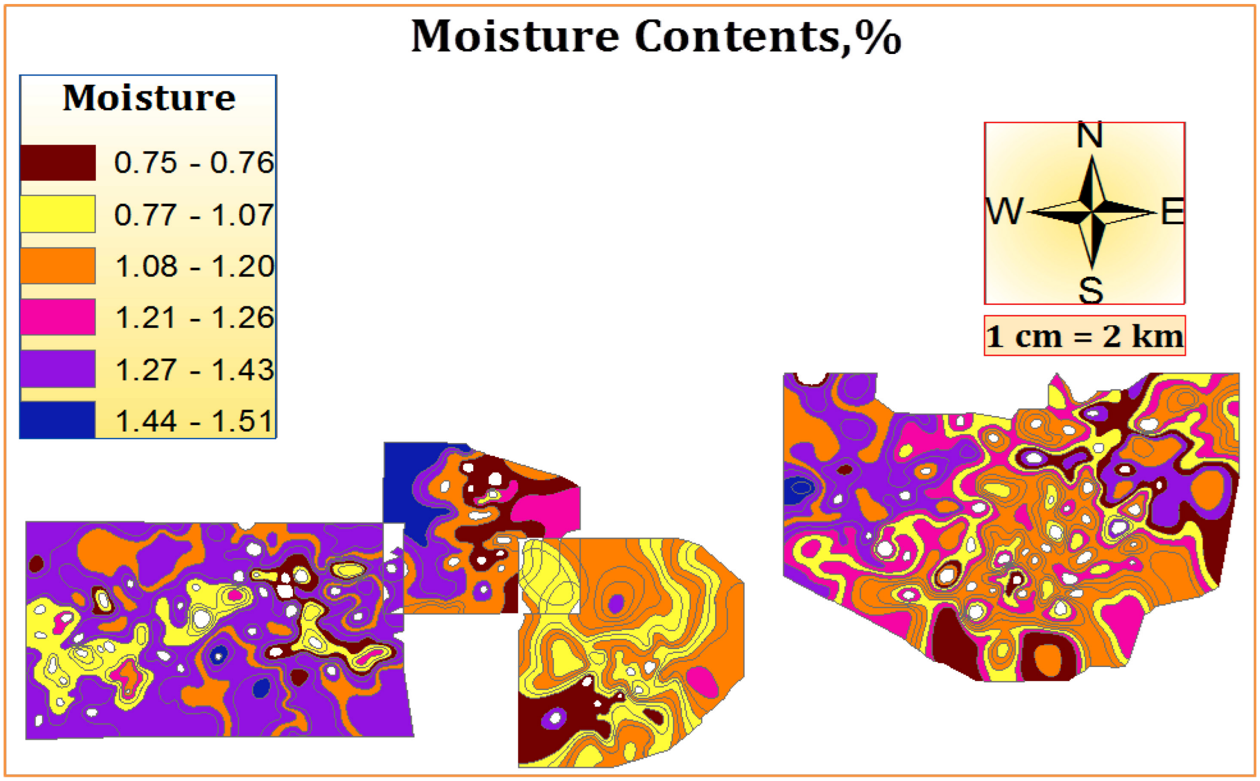


Figure 5.8: Moisture content of coal, %

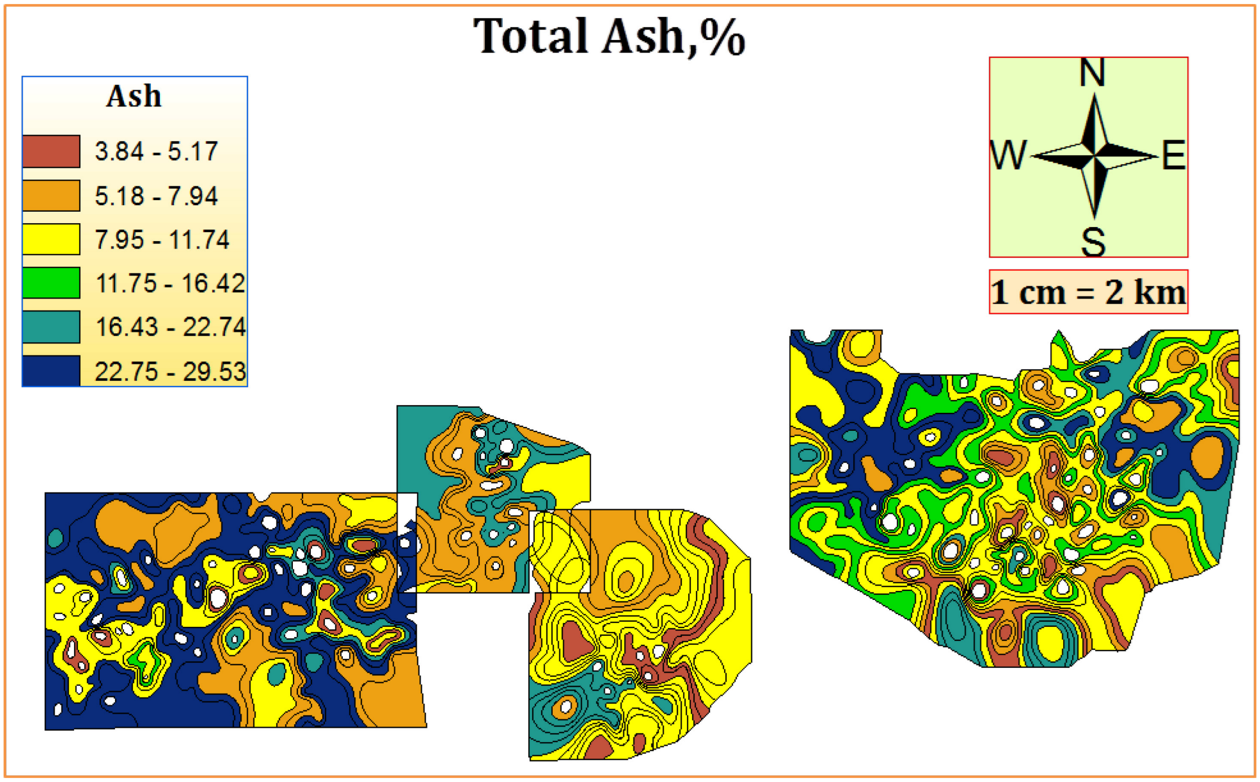


Figure 5.9: Ash yield of coal, %

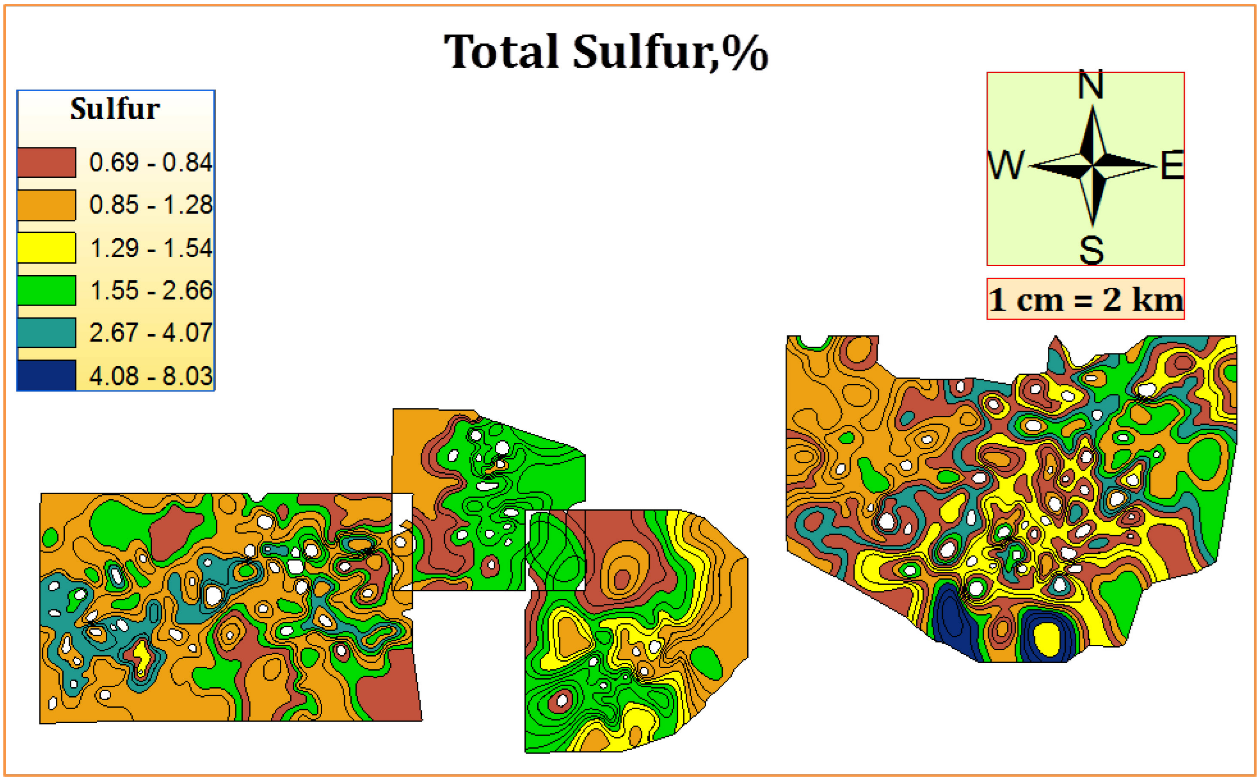


Figure 5.10: Total sulfur content of coal, %

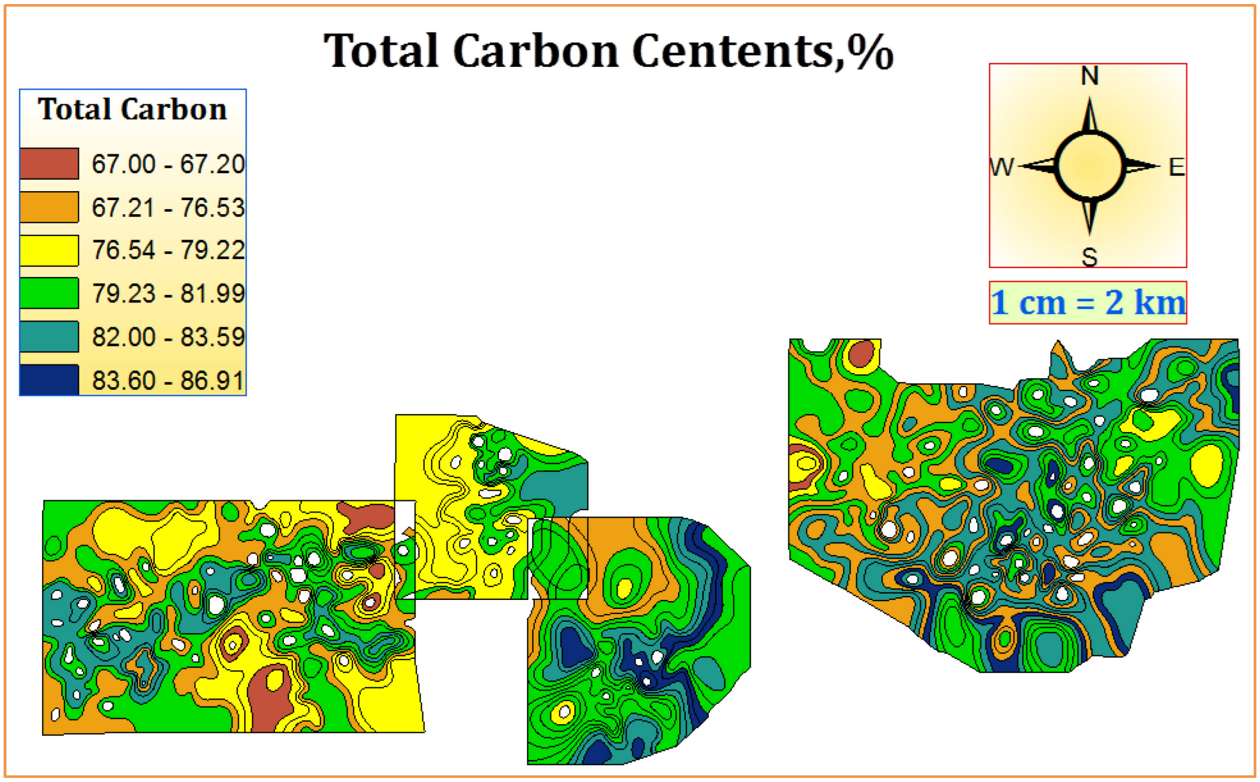


Figure 5.11: Total carbon content of coal, %

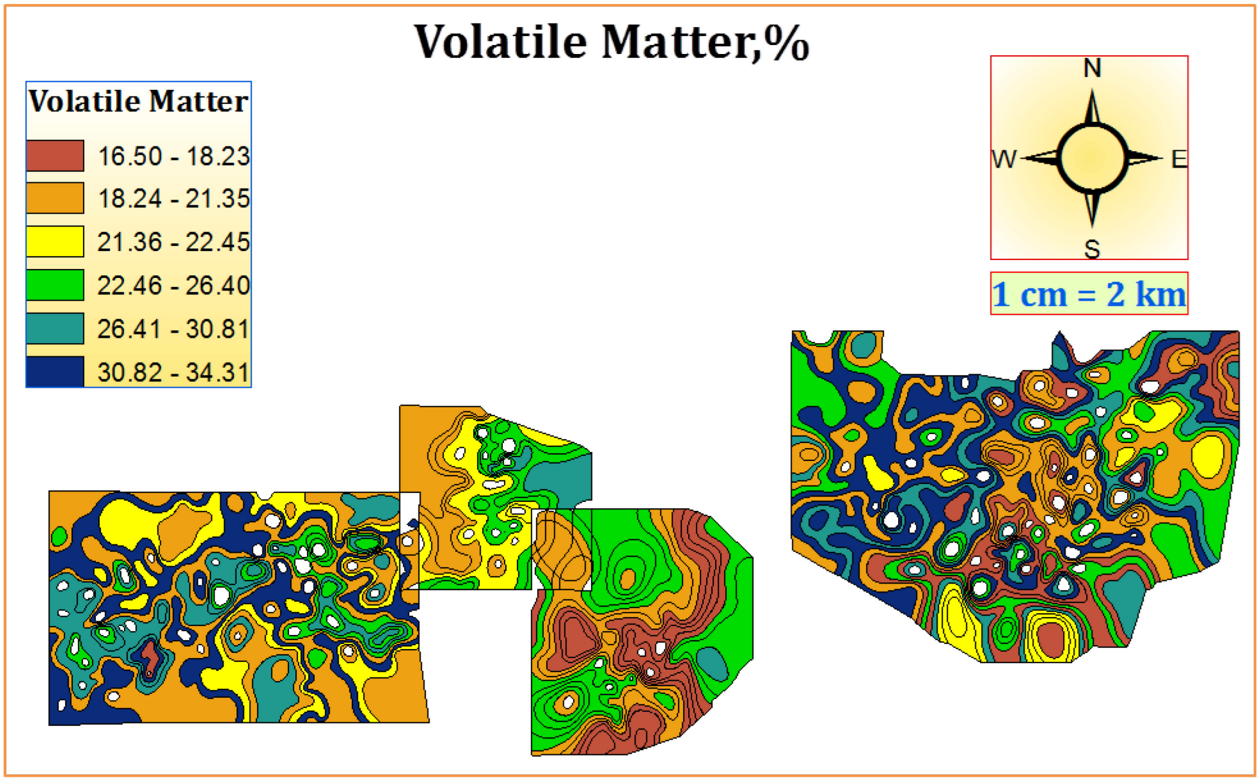


Figure 5.12: Volatile Matter of coal, %

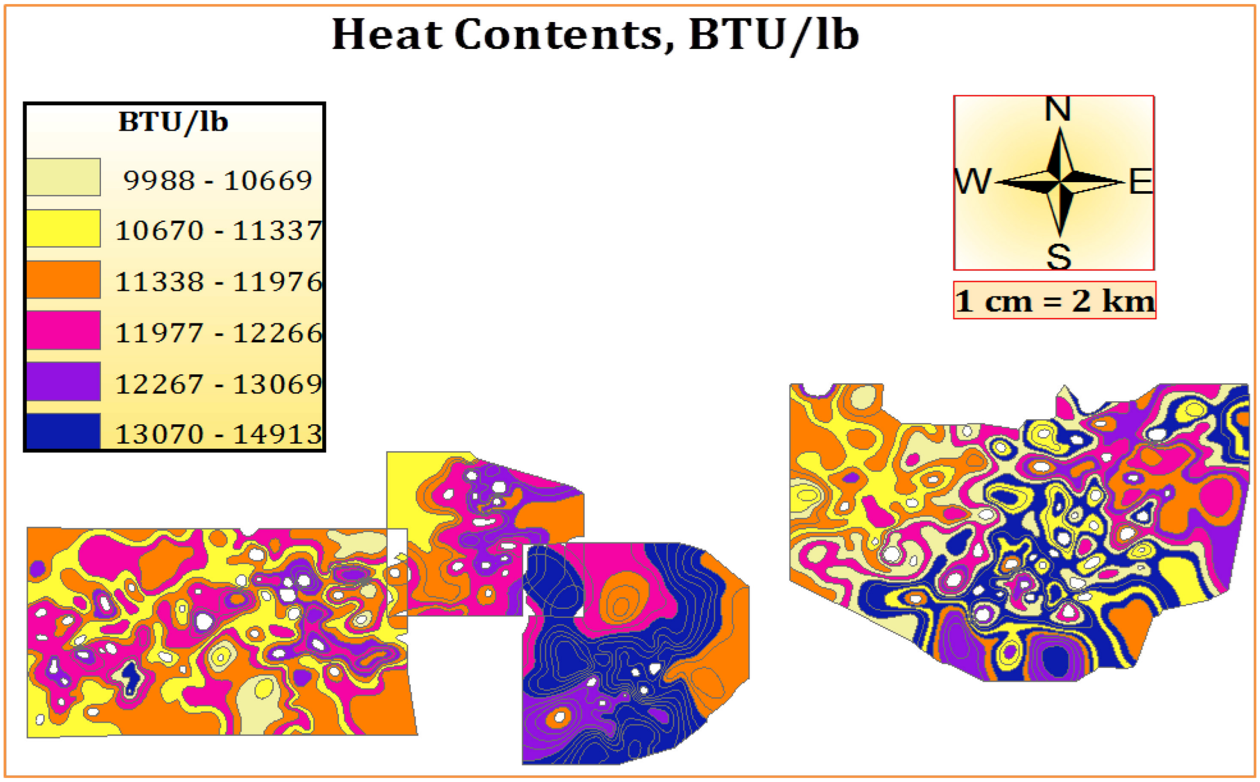


Figure 5.13: Heating value of coal, BTU/lb.

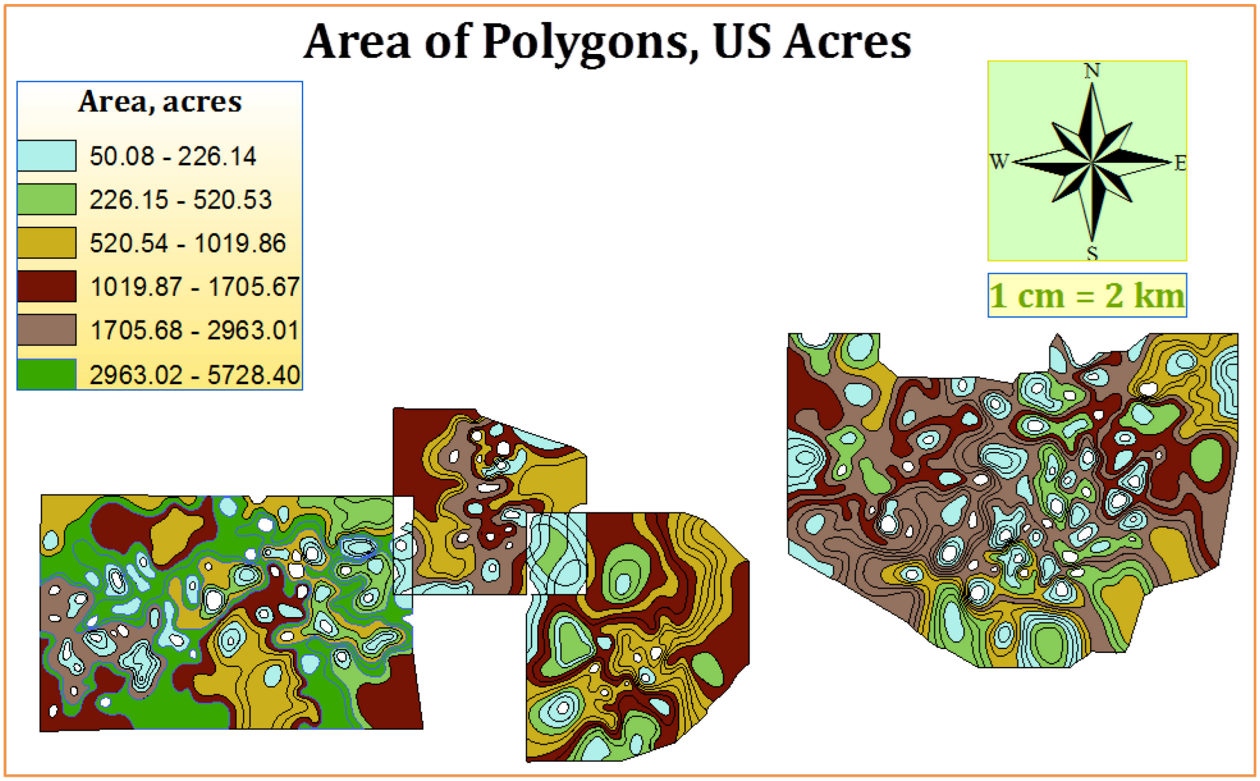


Figure 5.14: Area polygons in acres

Major highways and railroads were clipped from the regional area to show only those passing through or closer to the study area. Similarly, elevation and land cover data obtained from the USGS website [USGS 2011] and National Land Cover Database 2006 (NLCD) from Multi-Resolution Land Characteristics Consortium [MRLC. 2011] was clipped for the study area. The NLCD data was used to locate the agricultural lands, surface water bodies, residential and developed areas and forests. The streams and water body data was from the National Map Viewer [USGS 2012] and aquifer information was obtained from the National Water-Quality Assessment (NAWQA) Program website managed by USGS. The data showed that three distinct aquifers were located in the area [NAWQA. 2012]. The map layers of this data are shown below (Figures 5.15 - 5.17).

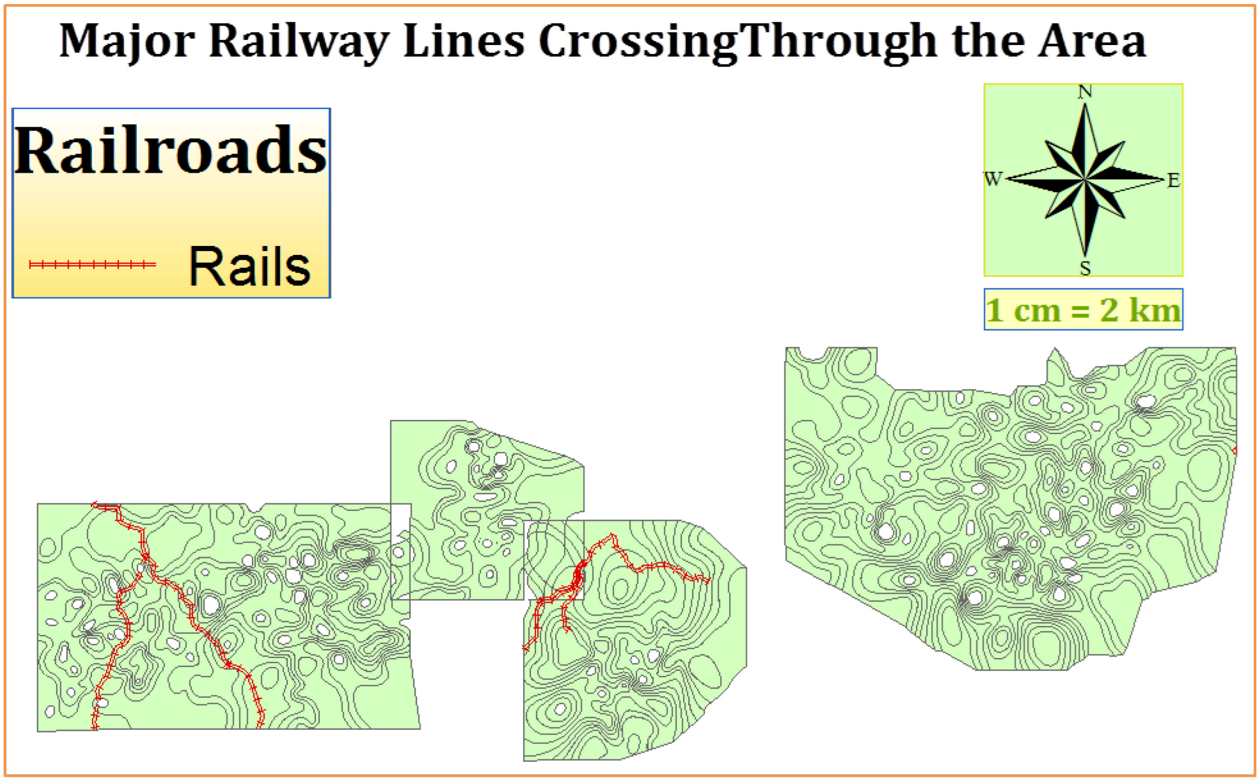


Figure 5.15: Major railroads through the area

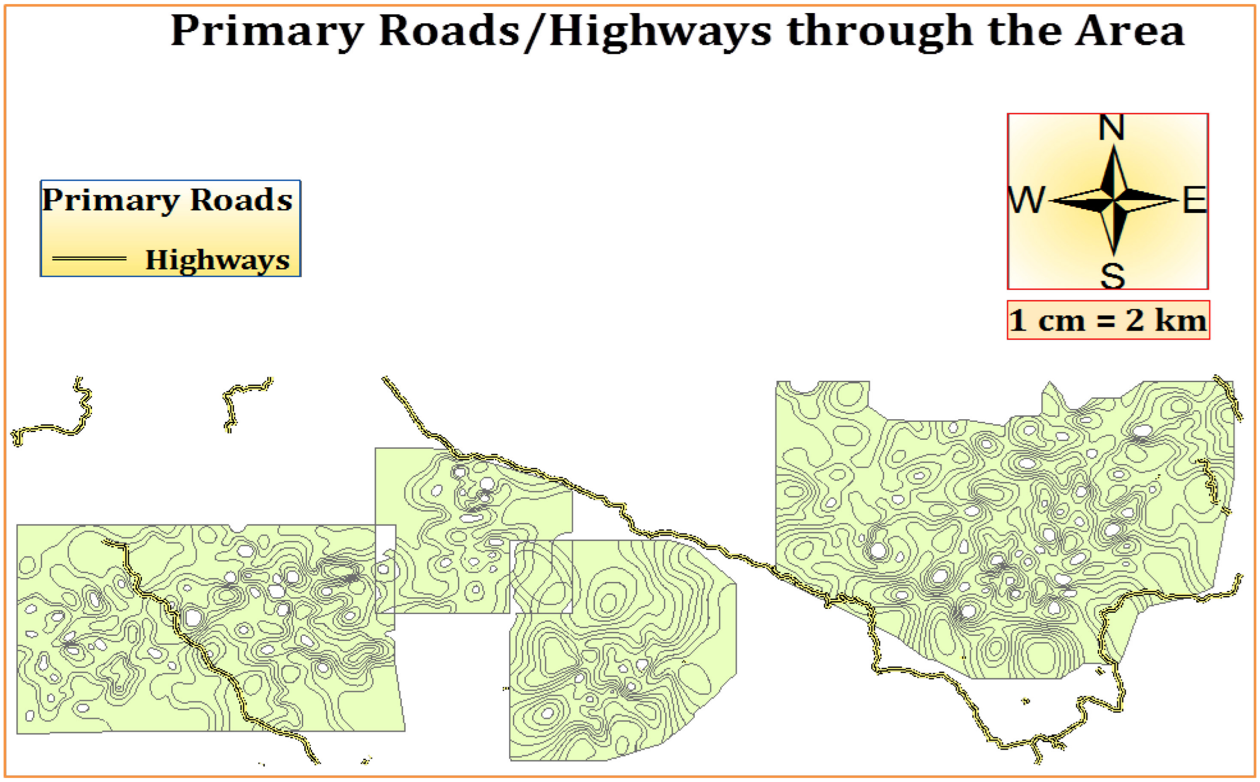


Figure 5.16: Major Highways through the area

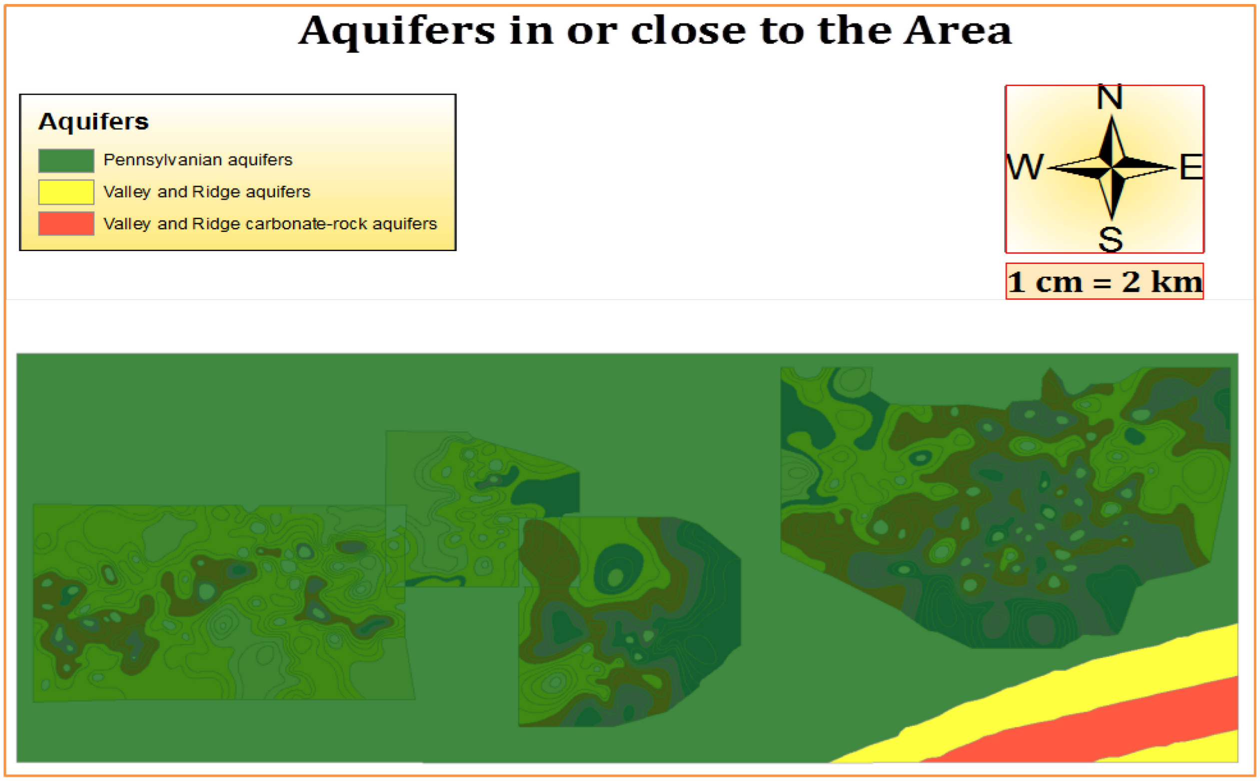
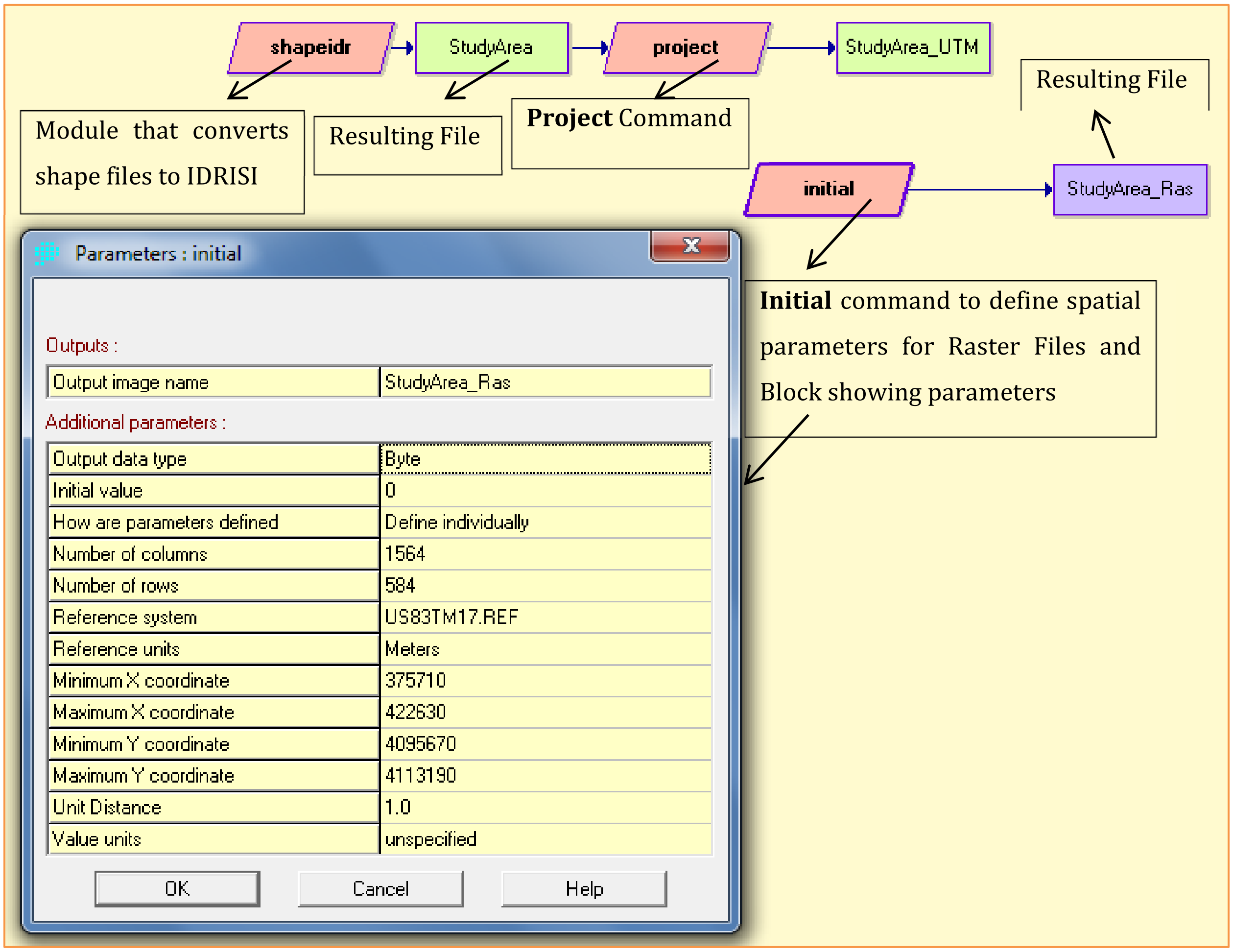


Figure 5.17: Aquifer close to the area

5.8 Working in IDRISI

The raster data was organized in IDRISI for preparation, displaying and subsequent use for the decision model. The NLCD, digital elevation data (DEM), topographic data was already in the raster or geo-tiff format, however all other layers and polygons data was in the vector shapefile format. In order to import this data, the module shown in Figure 5.18 was used. This part of model imported shapefiles to IDRISI, projected them to Universal Transverse Mercator (UTM) zone 17 for Virginia and converted them to raster. For conversion into raster, an initial raster file using the "Initial" command of IDRISI was used. The spatial parameters were defined as per coordinates of the existing polygon file. To cover the entire study area, 1564 columns and 584 rows with a cell size of 30 m x 30 m were created. This initial file was used to specify spatial parameters for subsequent data layers.



Module that converts shape files to IDRISI

Resulting File

Project Command

Resulting File

Initial command to define spatial parameters for Raster Files and Block showing parameters

Outputs :

Output image name	StudyArea_Ras

Additional parameters :

Output data type	Byte
Initial value	0
How are parameters defined	Define individually
Number of columns	1564
Number of rows	584
Reference system	US83TM17.REF
Reference units	Meters
Minimum X coordinate	375710
Maximum X coordinate	422630
Minimum Y coordinate	4095670
Maximum Y coordinate	4113190
Unit Distance	1.0
Value units	unspecified

Figure 5.18: The module for preparing shapefiles into IDRISI format

Some of the resulting raster images are shown in Figures 5.19 - 5.20. All the data was converted into Raster Images after importing from shapefiles and GeoTiffs and the modeling was done in the IDRISI based on these raster data images.

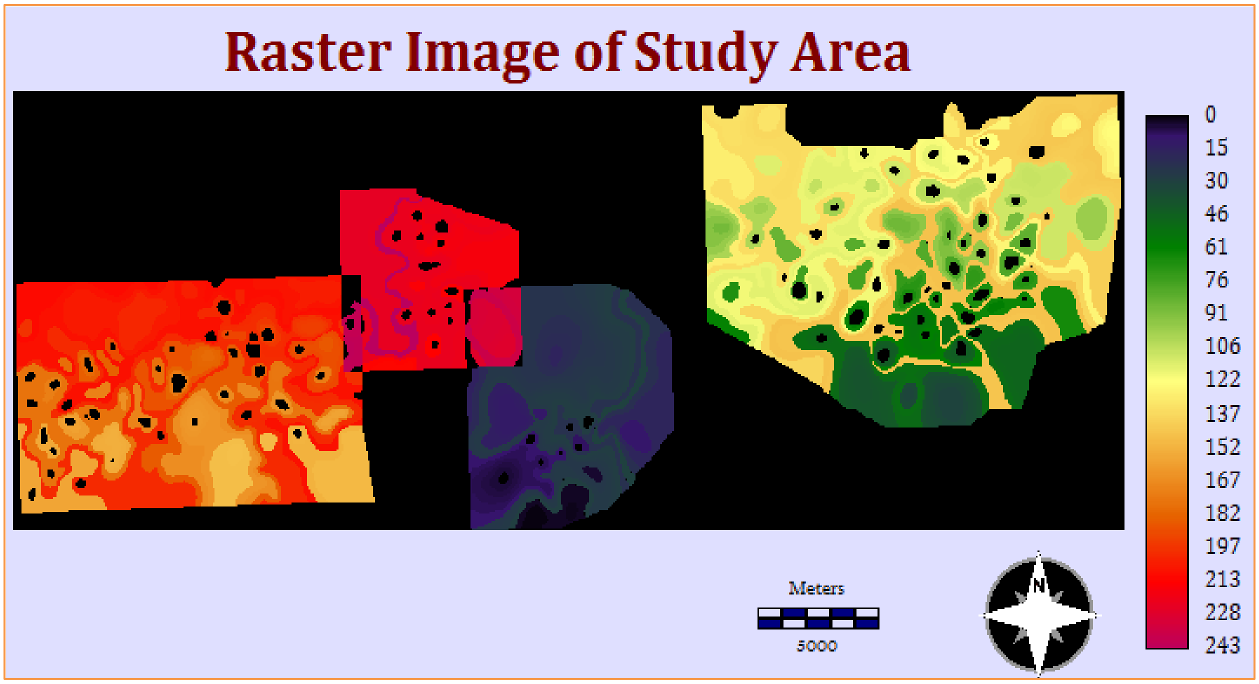


Figure 5.19: Raster image of the area polygons created by importing shapefile to IDRISI

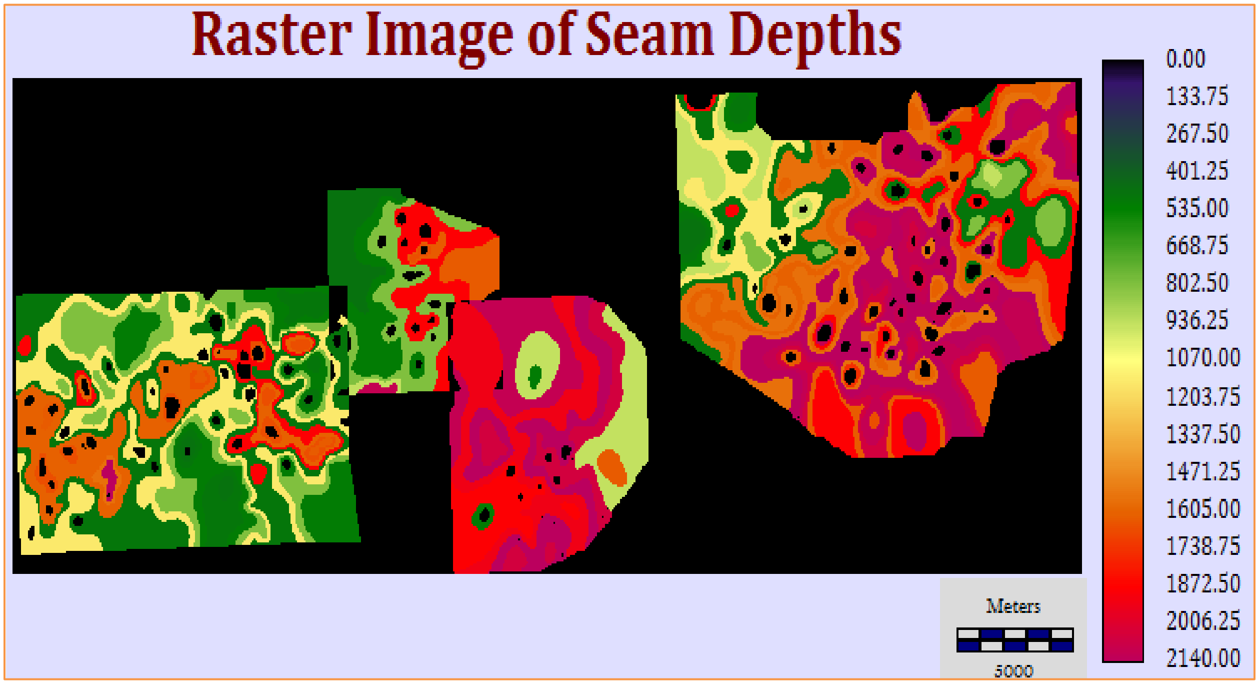


Figure 5.20: Raster images after preparation in IDRISI

The aquifer data was in shapefile format in geographic coordinate system for the entire Virginia State. It was projected to UTM Zone 17, converted to raster and then clipped to the study area using "Window" command of IDRISI. The NLCD and NED data was in Geo-tiff format. NED data was in Latitude Longitude at NAD 83 and NLCD was in Albers conical equal area projection. Both were projected to 1983 UTM 17 and clipped to the desired area. The modules/sub models for this portion are shown in Figure 5.21 and Figure 5.22.

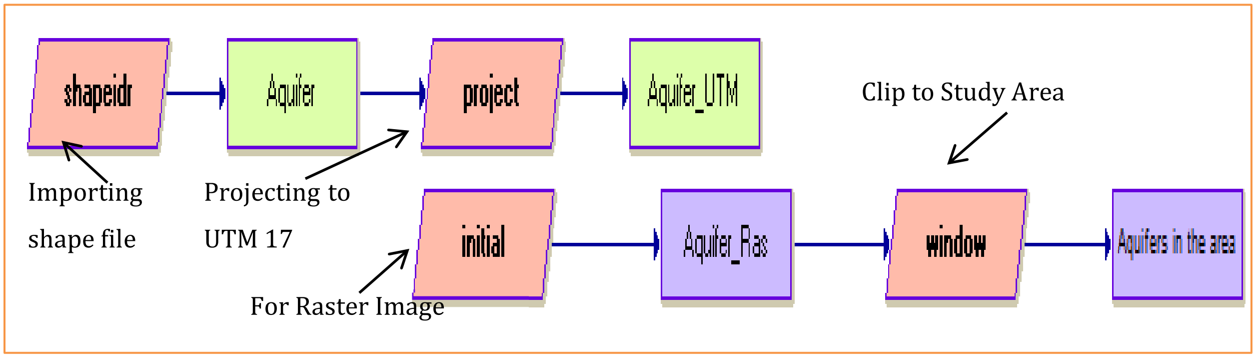


Figure 5.21: Module to import the aquifers in the study area

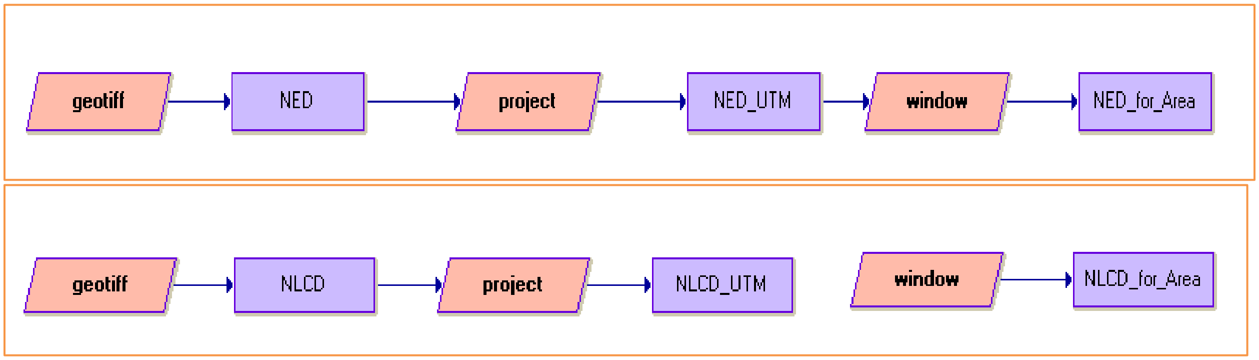


Figure 5.22: Module to import NLCD and NED Geo-tiff files for the study area

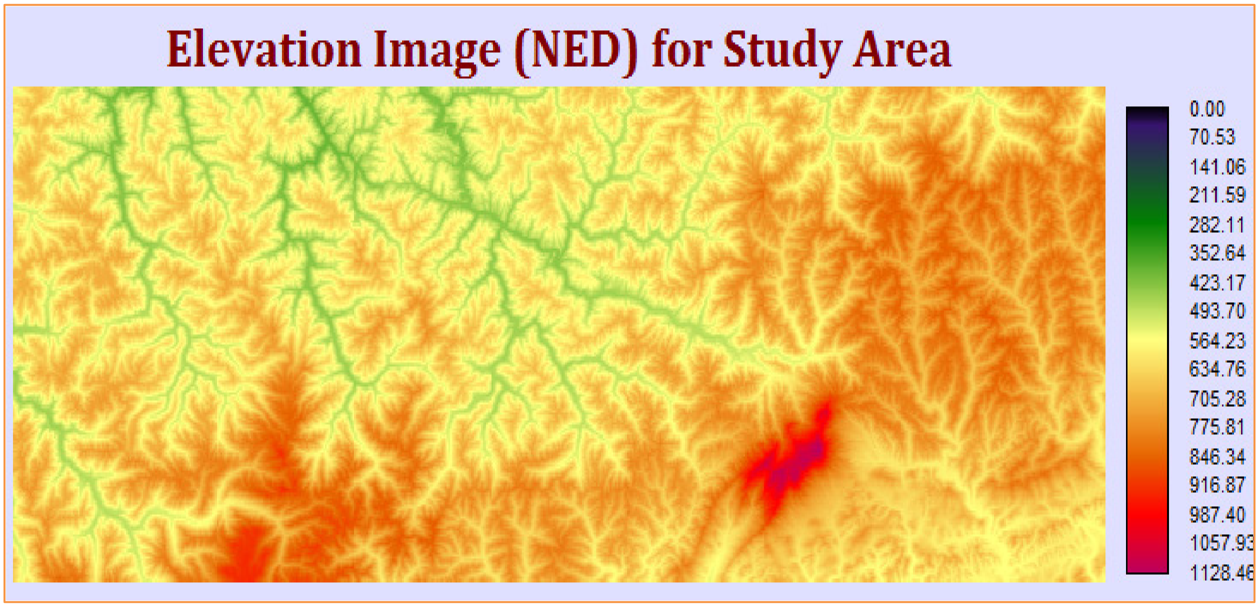


Figure 5.23: Elevation image of the area

To import forests, developed areas and agricultural lands, the "Reclass" command was used, giving a value of '1' to the desired features and value of '0' for all other features. For example in the following model , the reclass file was created giving a value of '1' to features '41 & 42' that represent evergreen and deciduous forests, whereas all other features were reclassed as '0'. The model and resulting images are shown in Figures 5.24 to 5.27.

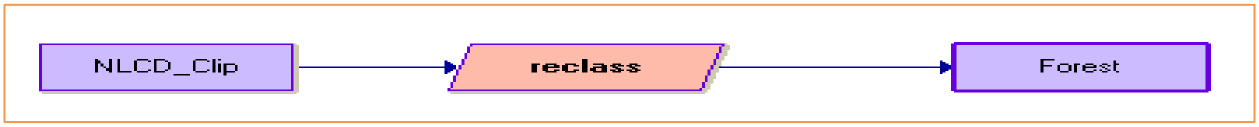


Figure 5.24: Creation of forest image from NLCD data

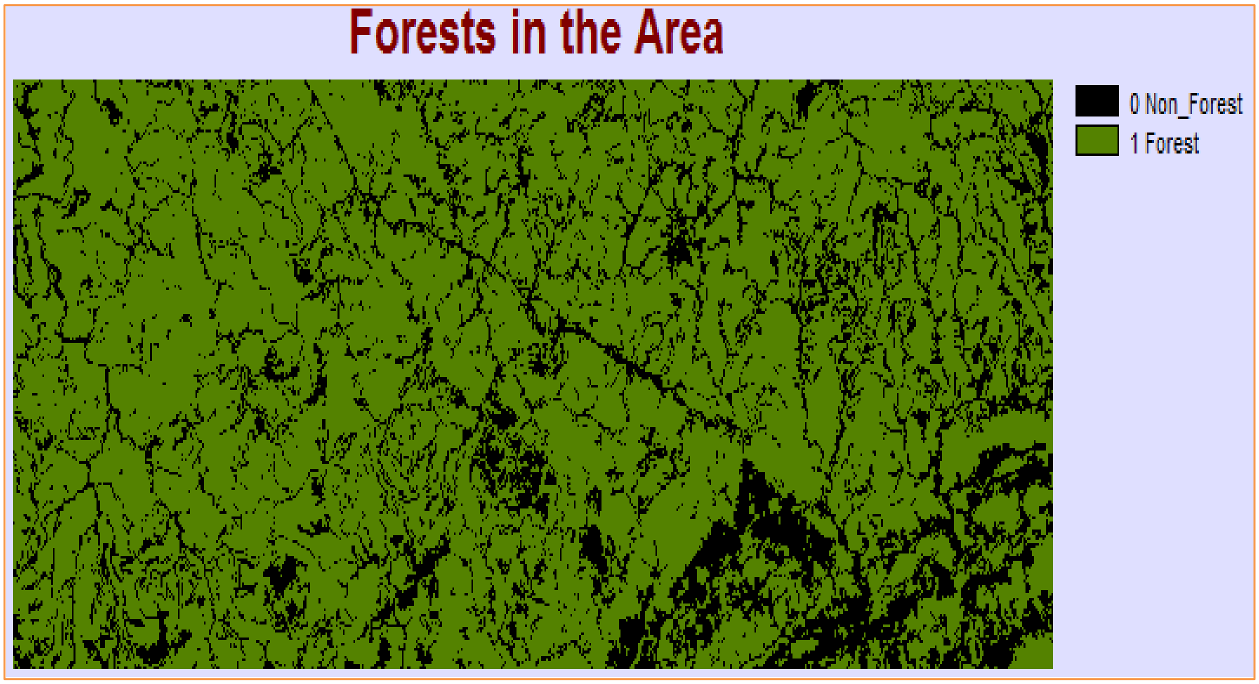


Figure 5.25: Boolean image of forests in the area from NLCD

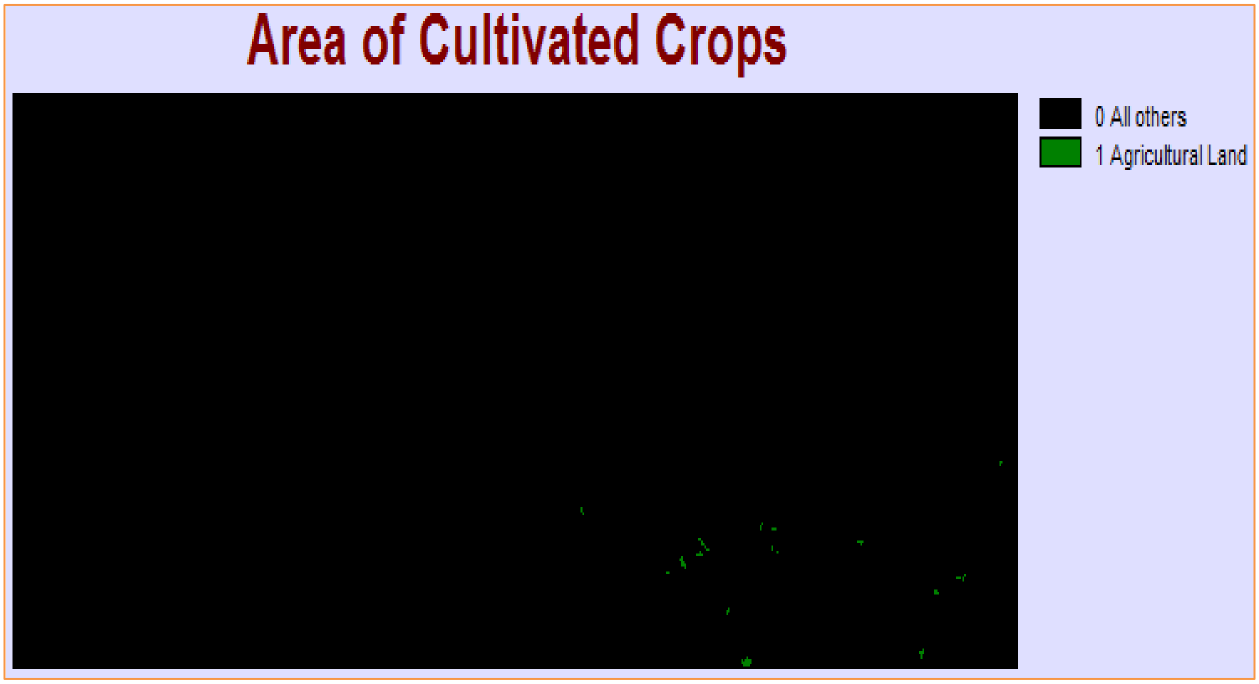


Figure 5.26: Boolean image of crops land from NLCD

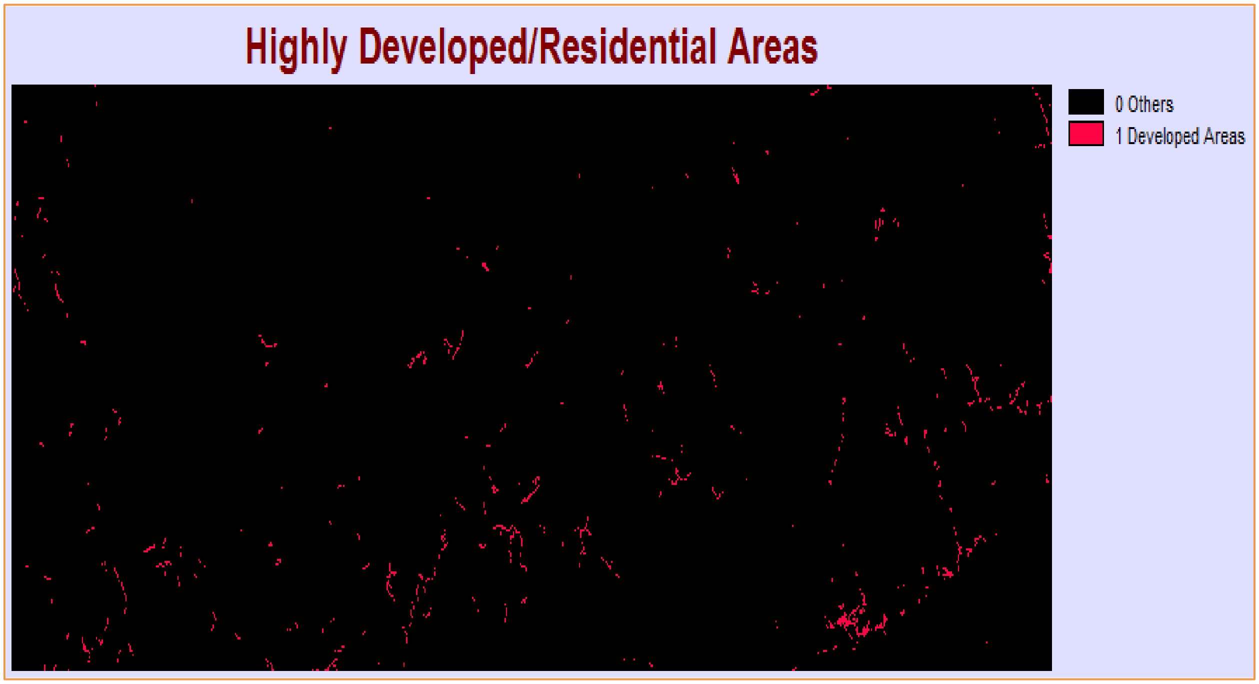


Figure 5.27: Boolean image of highly developed/residential area from NLCD

5.9 Distance Images

The distance from agricultural land or crops, residential areas or highly developed commercial areas, roads, railway lines and potable aquifer is more meaningful for analysis and planning purposes rather than the physical presence of these features in the area. Thus, the distance images for these features were created for ranking in the decision model based on distances. The module used to develop these images is shown in Figure 5.28 and the distance images of different features are shown in Figures 5.29 to 5.31.

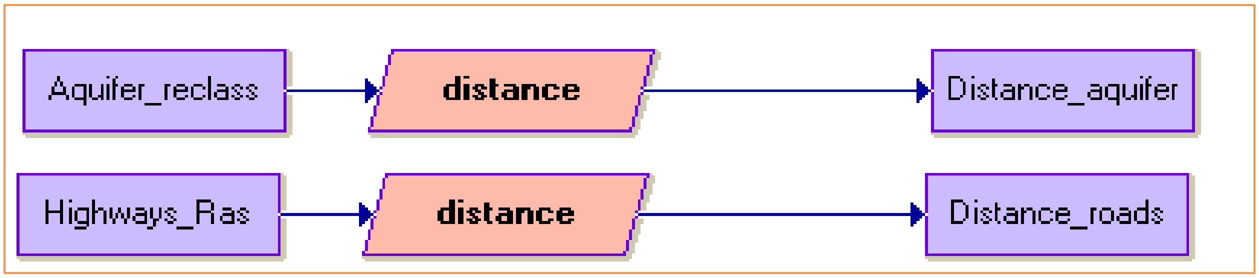


Figure 5.28: Module to develop distance images for roads, aquifer and railways

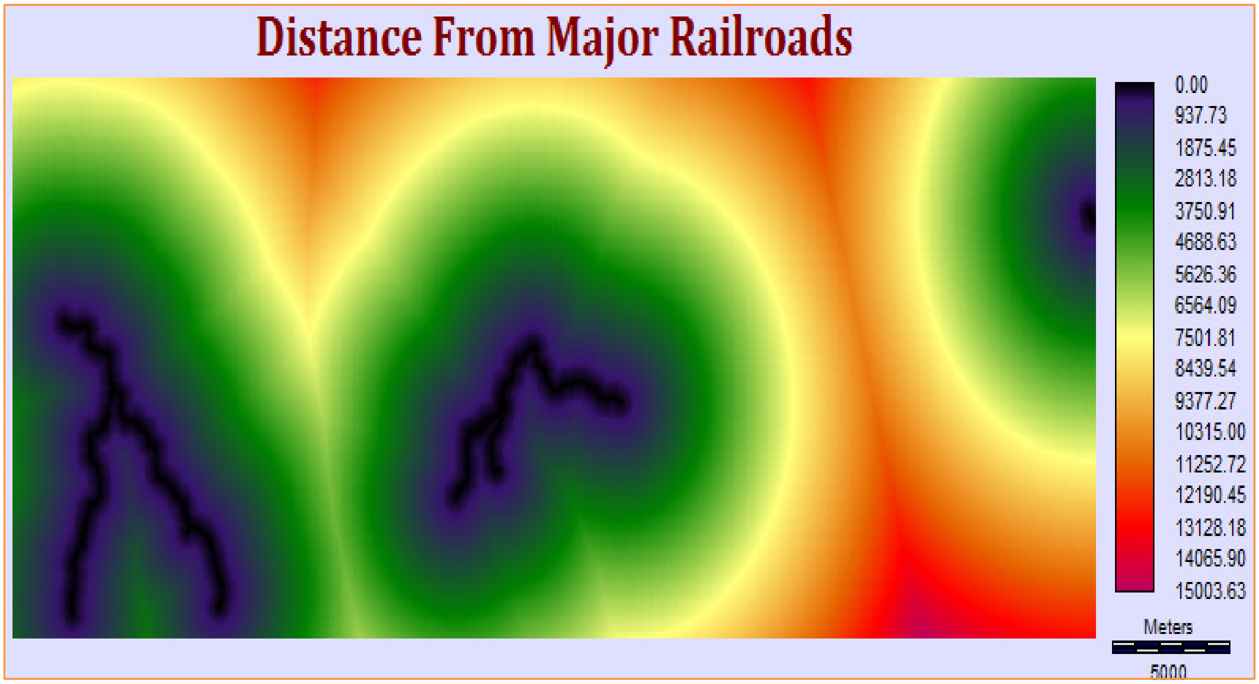


Figure 5.29: Image showing distances from railway lines

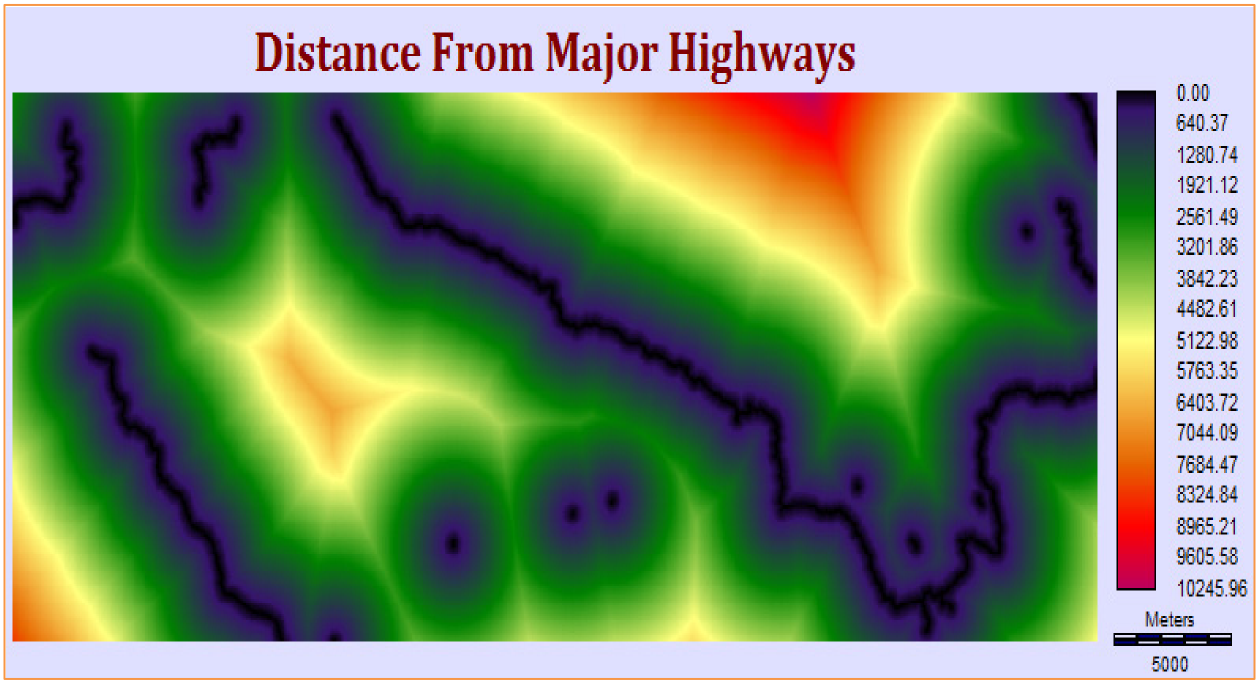


Figure 5.30: Image showing distances from primary roads

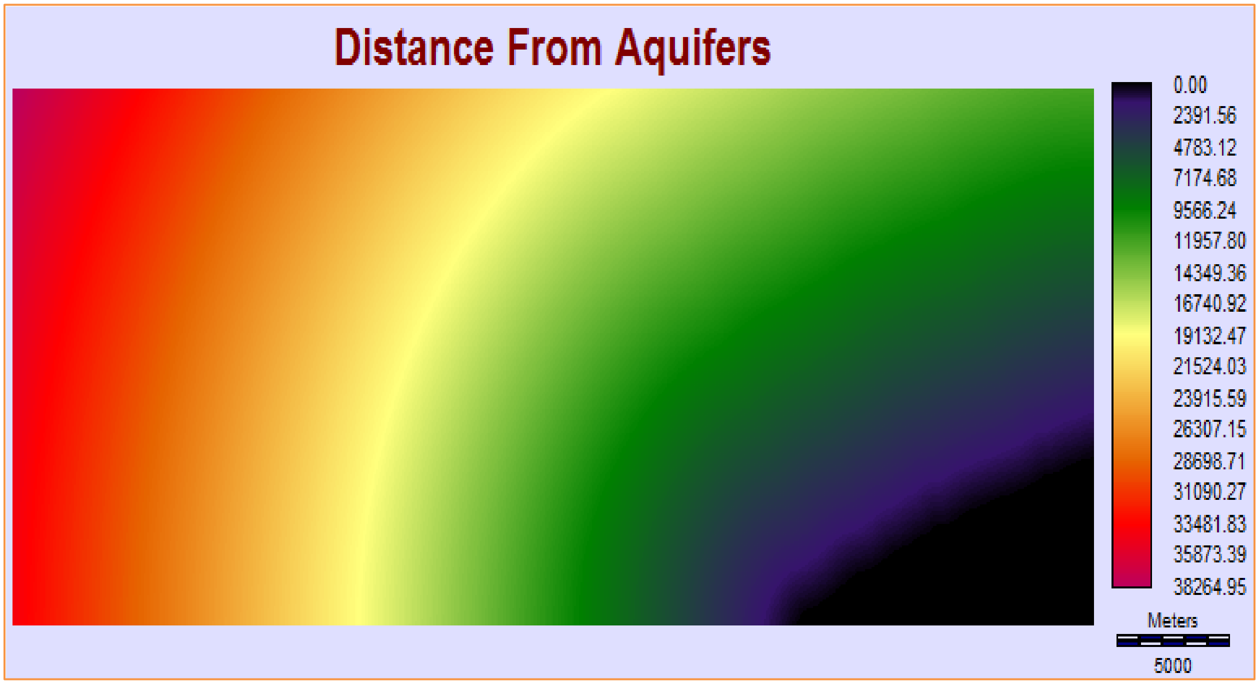


Figure 5.31: Distance image for aquifers

For crops land, residential areas and water bodies, images with buffers around those features were developed instead of distances. As these factors were set as constraints for the site selection model, any areas falling within the buffer zone was unsuitable for selection. Buffer distances of 500 m around crops and residential areas and 100 m around major water bodies were used. The resulting images are shown in Figures 5.32 to 5.34.

Figure 5.32: 500 m buffer around crops

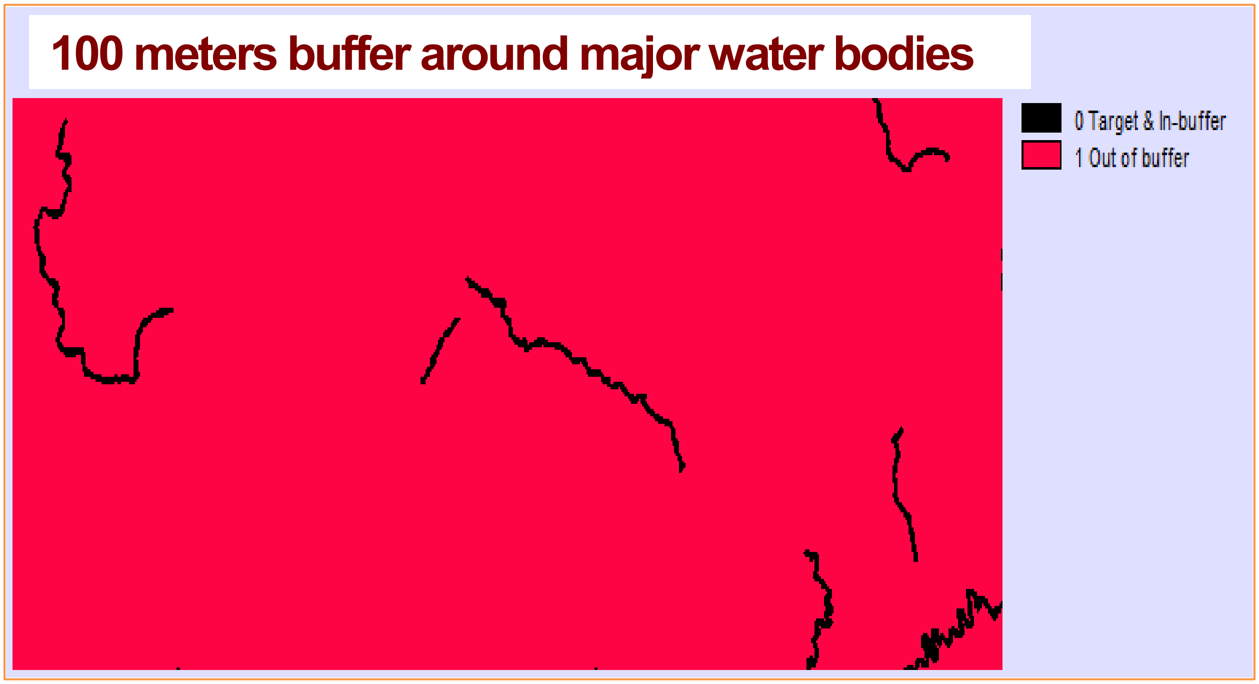


Figure 5.33: 100 m buffer around major water bodies

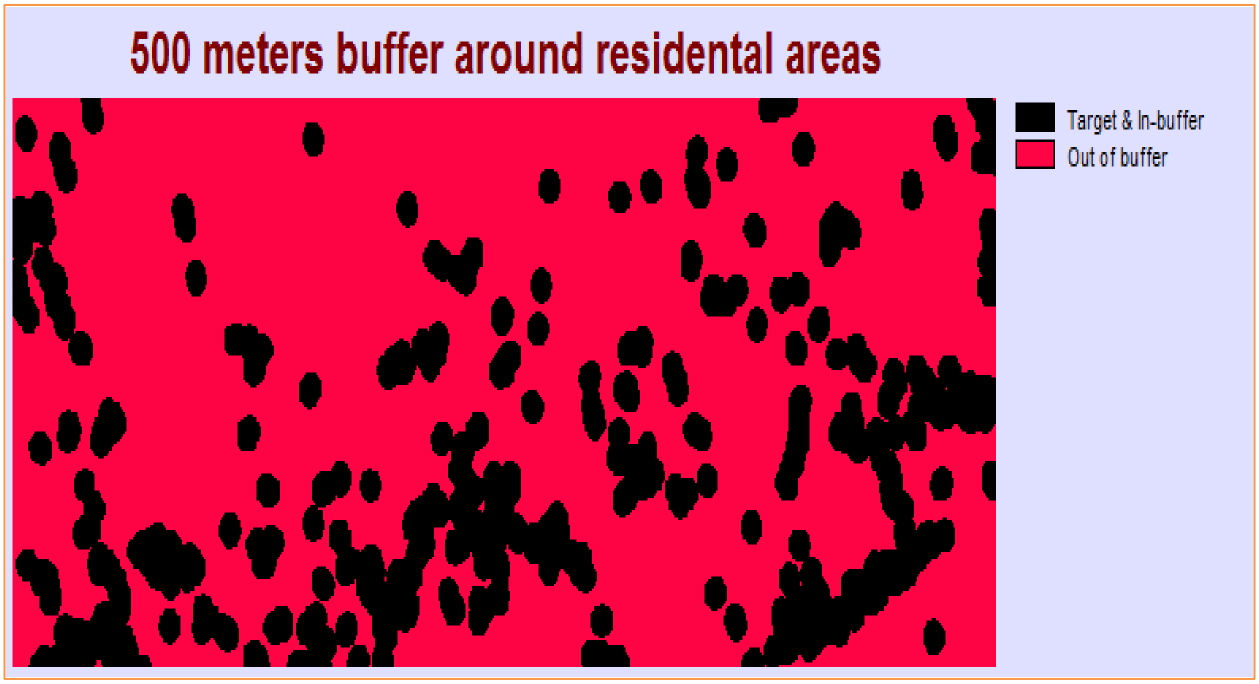


Figure 5.34: 500 m buffer around residential areas

5.10 Modeling

After preparation of data layers and data images, actual modeling for site selection was carried out. The first step in modeling was classification of factors for further analysis and use in the model. The procedures described herein for the modeling are based on the modules from IDRISI software[Clark Labs 2012]

5.10.1 Classification of Factors

For modeling, the data layers were divided into three parts.

i. The factors that trade off
ii. The factors that do not trade off
iii. Constraints

5.10.1.1 Factors that Tradeoff

These factors enhance the suitability of site and it is preferred if these are available at the site, however they are allowed to tradeoff in such a way that one factor can compensate for the shortcoming of any other factor or factors. The level of trade off defines the degree to which one factor can make up for the lack of other factors. The weight of the factors defines the level of trade off for each factor. In this category, the following data layers were included.

i. Moisture content
ii. Ash
iii. Sulfur
iv. Carbon content
v. Volatile matter
vi. BTU per pound
vii. Coalbed methane and gas content
viii. Forests (instead of using forests, a distance image from forest was used)

5.10.1.2 Factors that do not Tradeoff

These factors are very important for the site selection and form the basis of site selection criteria. These are equal in weight and importance and therefore cannot be allowed to compensate for the lack or excess of one another and they all must be present at reasonable level to declare the site most suitable for the project. That is why these factors are not allowed to tradeoff and are assigned equal weights in making the decision rule. The following data layers were included in this category

i. Coal rank
ii. Seam thickness
iii. Seam depth
iv. Seam inclination/dip
v. Permeability
vi. Hydrology of the area
    - Presence of aquifers
    - Major Water bodies
vii. Infrastructure availability
    - Distance from Primary Roads
    - Distance from Railroads

5.10.1.3 Constraints

Constraints are also called crisp factors [Carstensen 2011]. These criteria must be met for a site to be suitable for selection. These are Boolean factors in either "YES" or "NO" having a value of '0' or '1'. These are generally imposed either by regulatory restrictions or by company policies. In this category the areas covered by crops and developed/residential areas were included. The area within 100 m of a major water body was also set as a constraint for site selection.

5.10.2 Standardization of Factors

The data layers selected for modeling were in different units. It is difficult to compare and weight the data when they are in different units. For this purpose standardization of factors was done. For constraints, the data is either '0' or '1', where '0' means not included in the decisions set and '1' means included in the selection criteria. However, for factors the standardization was done through "Fuzzy membership", where all the data was set to the same scale range of 0-225. Fuzzy membership is based on different membership curves. Linear or straight-line interpolation membership is very sharp from membership to non-membership. J-shaped membership function gives a rapid drop in the membership either immediately or at the end of the curve. S-shaped or sigmoidal curve gives a good range of models and is very popular[Carstensen 2011]. The standardization process is discussed in detail for each factor, in the model building stage.

5.10.3 Factors Weights

Different factors have different significance when it comes to include them in the selection decision, therefore weighting them accordingly is very critical. In this model, Saaty Analytical Hierarchy Process (AHP) was applied for determining the weights. These weights were based on opinions and estimations from literature and were then statistically checked for consistency. These assigned weight values were combined in a pairwise comparison matrix and a principle components analysis was run on the pairwise matrix to provide a measure of optimal weights and a check for the consistency of the comparison [Carstensen 2011]. The process is elaborated in detail in the model building stage.

5.10.4 Trade off levels and Risk Assessment

The level of tradeoff allowed between factors, factor weights and relative balance of factor weights determine the amount of risk that the site selected for the project is suitable in reality or not. Levels of tradeoff and factors weights determine the risk between the extreme levels of very risky and very risk averse scenarios. In IDRISI, the module Multiple Criteria Evaluation (MCE) helps the user to define the level of tradeoff and risk. Three MCE procedures are most common[Carstensen 2011].

5.10.4.1 Boolean Intersection

In the Boolean intersection, all the factors are constraints or crisp factors with values either '1' or '0'. This constraint-based model provides extreme cases of risks in the decision i.e. very risky or very risk averse. There is no tradeoff between factors and no factor can make up for the lack of the other. It combines the factors in two ways,

a. AND Overlay

'AND' overlay is very risk averse or least risky model in which all the constraints need to be met to place a site in the suitability zone. There is no tradeoff between factors and the site must have everything required and defined by the selection criteria.

b. OR Overlay

'OR' overlay is opposite extreme of "AND" overlay where meeting only one constraint can put the area in the suitability zone and is therefore most risky. There is no tradeoff between factors as these are constraint-based models and constraints do not tradeoff.

5.10.4.2 Weighted Linear Combination

The weighted linear combination (WLC) allows complete tradeoff between factors and is therefore in the central zone of risk. The factors are weighted according to their importance in the criteria and highly weighted factors can compensate for lower weighted factors, however the lowest weighted factor still contribute in determining the suitability of sites. This model also allows constraints and after weighting and tradeoffs between factors, these are multiplied with the constraints to exclude the areas that do not meet the restrictions.

5.10.4.3 Ordered Weighted Average

Ordered weighted average (OWA) allows further control of trade off and risk by adding a second weighting to the process called order weights. In this case, the factors first are weighted differently to allow full tradeoff or all factors are assigned the same weight to prohibit tradeoff between factors. Then a second weight is assigned to the factors that determine the risk and tradeoff between factors. The relative balance of order weights places the risk factor between extremes of "AND, risk-averse" or "OR, very risky" overlays and tradeoff levels between "No tradeoff" to "Full tradeoff". The triangle in Figure 5.35 represents the ordered weights strategy.

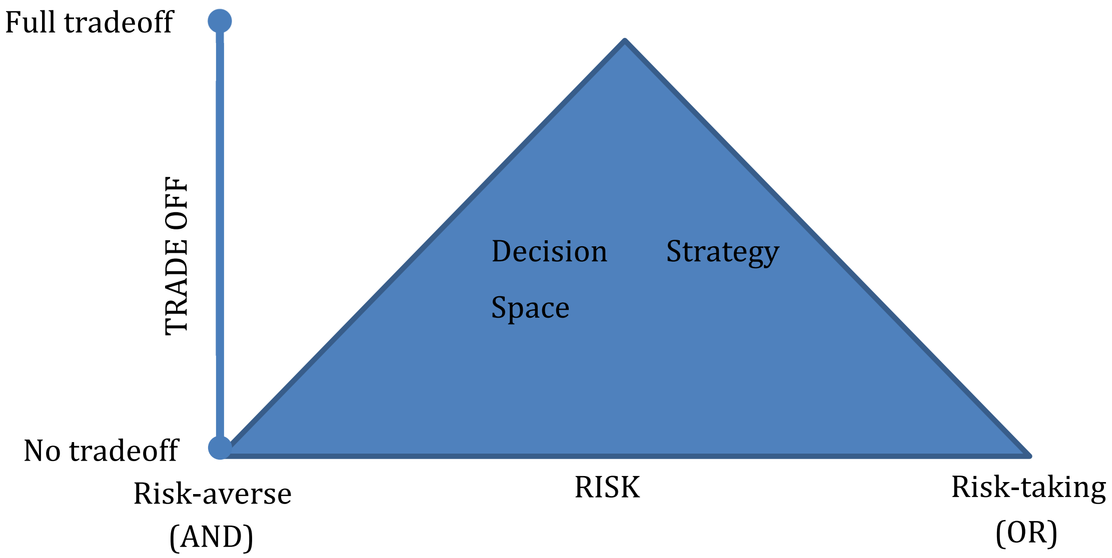
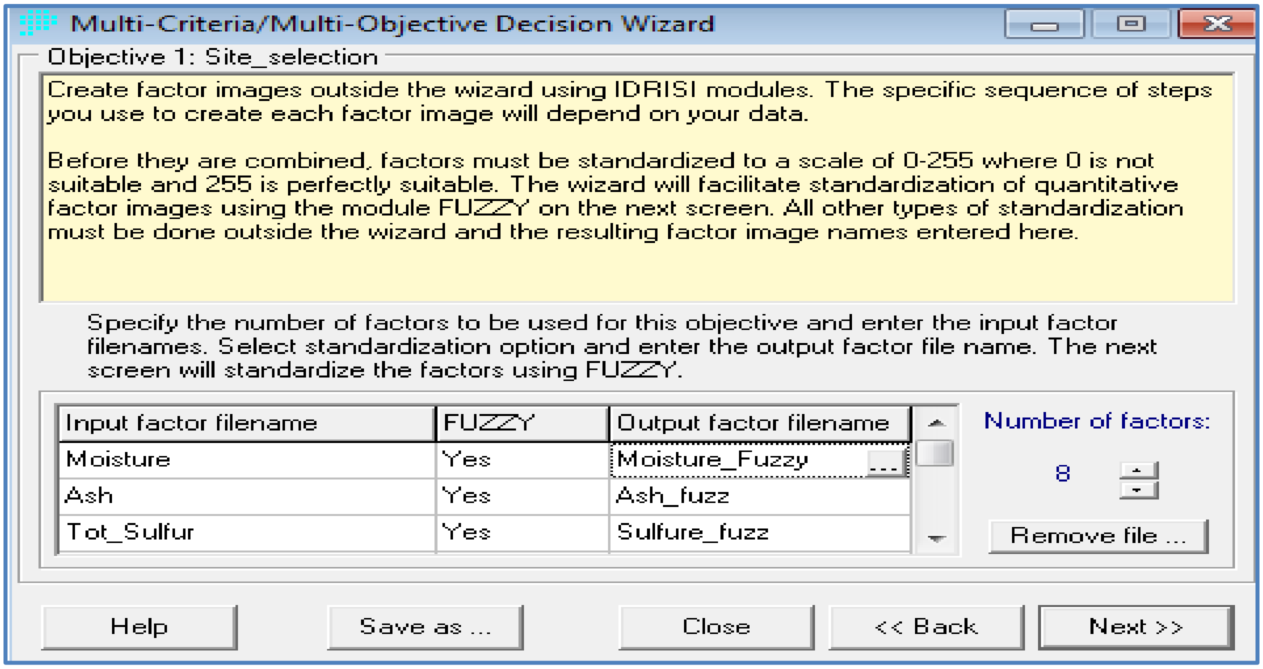


Figure 5.35: OWA triangle

5.11 Decision Model

The decision wizard of IDRISI was used to build the decision model. First of all the factors that do not trade off were run through the decision wizard. For these factors, appropriate weights were chosen through WLC and these were allowed to fully trade off by choosing "No OWA" which is equivalent to the top of OWA triangle with full trade off and average risk. At this stage, no constraint was used. The resulting image gave the combined effect of all the factors that tradeoff. Factors standardization was achieved using the "Fuzzy" command, the rules of which are discussed with each factor image. Figure 5.36 shows the start of the decision wizard, when the raster images of factors were imported into the wizard.



Create factor images outside the wizard using IDRISI modules. The specific sequence of steps you use to create each factor image will depend on your data.

Before they are combined, factors must be standardized to a scale of 0-255 where 0 is not suitable and 255 is perfectly suitable. The wizard will facilitate standardization of quantitative factor images using the module FUZZY on the next screen. All other types of standardization must be done outside the wizard and the resulting factor image names entered here.

Specify the number of factors to be used for this objective and enter the input factor filenames. Select standardization option and enter the output factor file name. The next screen will standardize the factors using FUZZY.

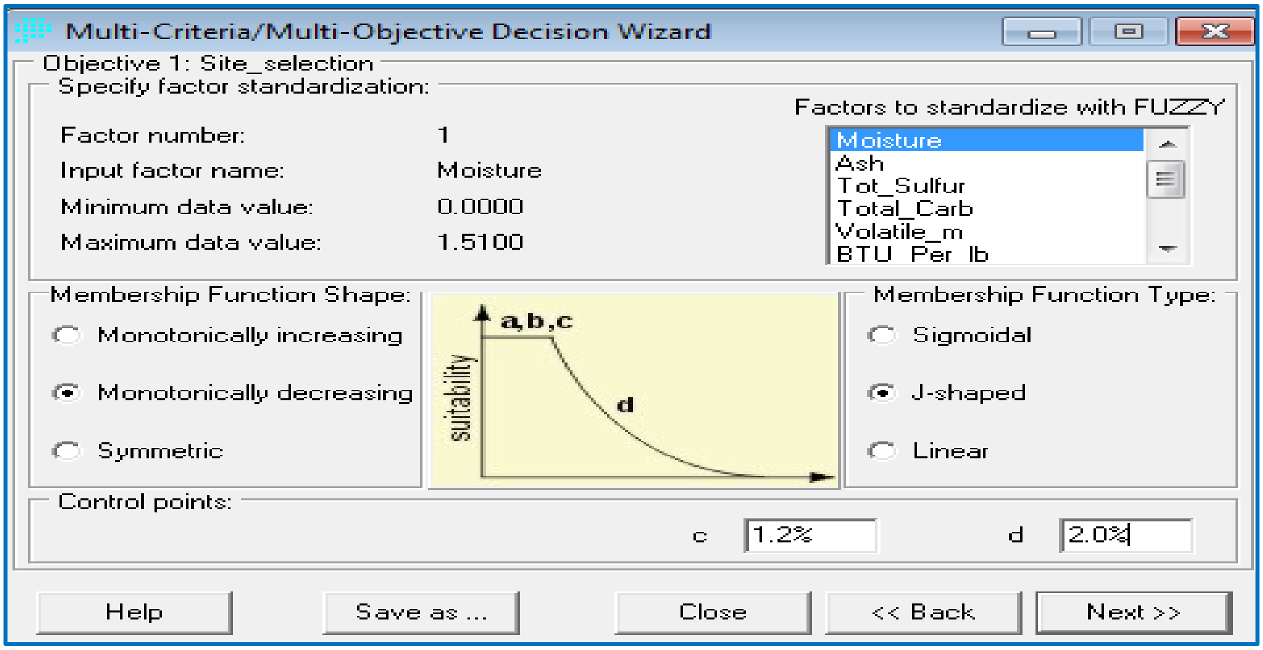
Input factor filename	FUZZY	Output factor filename
Moisture	Yes	Moisture_Fuzzy
Ash	Yes	Ash_fuzz
Tot_Sulfur	Yes	Sulfure_fuzz

Number of factors: 8

Figure 5.36: Importing factors in the decision wizard

5.11.1 Fuzzy Rules

After importing the factors that trade off to the decision wizard, the next step was to define fuzzy rules for each factor. For **moisture content** of coal, J shaped monotonically decreasing membership function was used to standardize the factor because some amount of moisture is required (>1%) in coal for the gasification process to take place and in determining the nature of the product gas [Walters and Nuttall 1977]. However, when the amount of moisture increases in the coal above 20% it obstructs the gasification process and can deteriorate the quality of gas. Thus, the J shaped monotonically decreasing function give highly suitable values for less moisture contents and then rapidly decreases the suitability after the moisture contents increase to a certain limit. As the moisture contents in this coal were relatively small (<2%), the J-shaped function for this factor was used with suitability rapidly decreasing after 1.2% (point c) and becoming zero at 2.0% or more moisture (point d). Figure 5.37 shows the screen shot of the image defining fuzzy rules for moisture content for standardization.



Multi-Criteria/Multi-Objective Decision Wizard

Objective 1: Site_selection

Specify factor standardization:

Factor number: 1
Input factor name: Moisture
Minimum data value: 0.0000
Maximum data value: 1.5100

Factors to standardize with FUZZY: Moisture, Ash, Tot_Sulfur, Total_Carb, Volatile_m, BTU_Per_lb

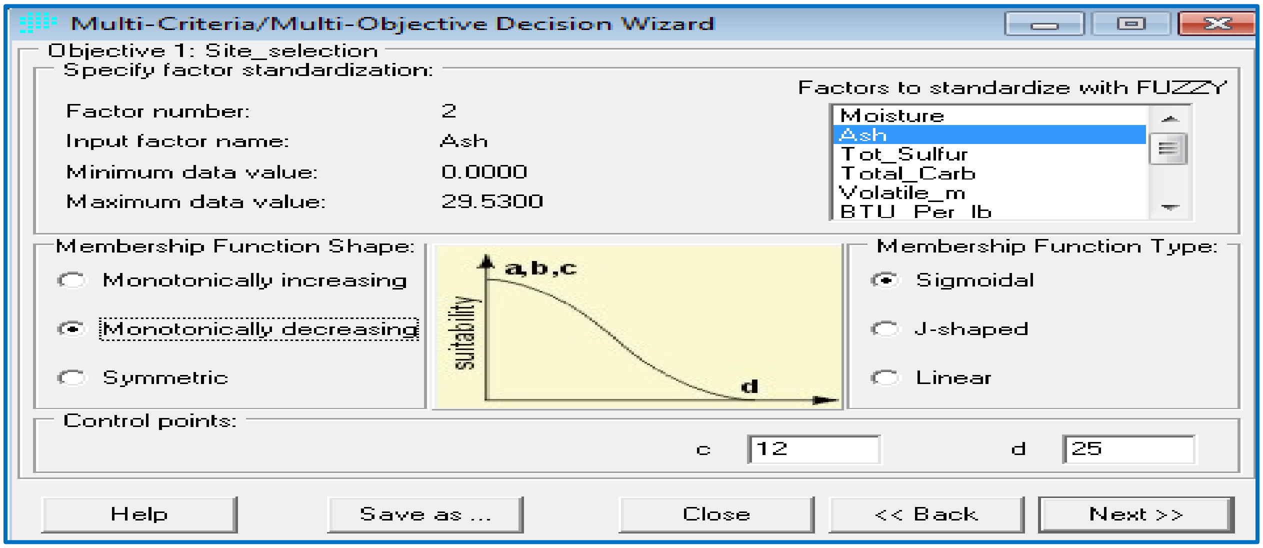
Membership Function Shape:
○ Monotonically increasing
● Monotonically decreasing
○ Symmetric

Membership Function Type:
○ Sigmoidal
● J-shaped
○ Linear

Control points: c 1.2% d 2.0%

Figure 5.37: Fuzzy rules for moisture contents

For **ash contents** of coal, the monotonically decreasing sigmoidal function was used, because the suitability of the site decreases gradually with the increase in the ash contents of coal. The site gradually loses its suitability when the ash contents increase from 12% (point c) and it is considered least suitable when the ash contents of coal increase to 25% (point d). Figure 5.38 shows the definition of fuzzy rules for ash contents of coal.



Multi-Criteria/Multi-Objective Decision Wizard

Objective 1: Site_selection

Specify factor standardization:

Factor number: 2
Input factor name: Ash
Minimum data value: 0.0000
Maximum data value: 29.5300

Factors to standardize with FUZZY: Moisture, Ash, Tot_Sulfur, Total_Carb, Volatile_m, BTU_Per_lb

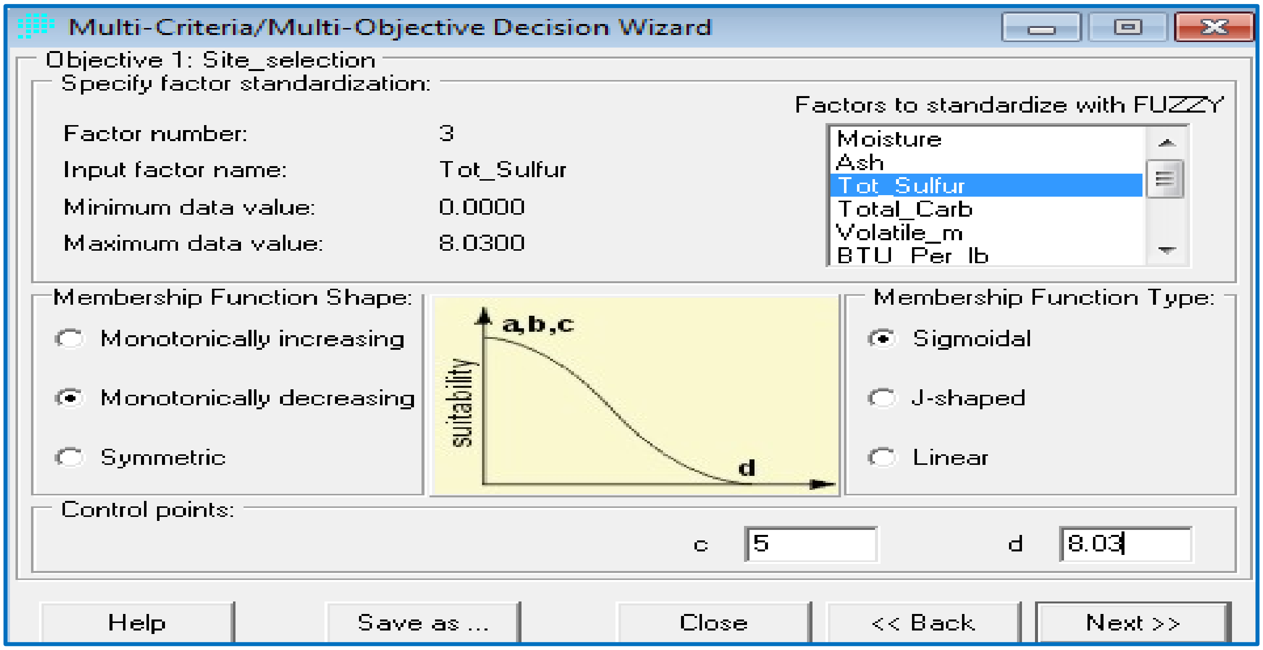
Membership Function Shape:
○ Monotonically increasing
● Monotonically decreasing
○ Symmetric

Membership Function Type:
● Sigmoidal
○ J-shaped
○ Linear

Control points: c 12 d 25

Figure 5.38: Fuzzy rules for ash contents

For **sulfur contents** of coal, the monotonically decreasing sigmoidal function was used, as the suitability of the site decreases with the increasing sulfur contents in the coal. Point c where the suitability starts to decrease was set at 5% and 8.03% (max. sulfur contents in this coal) was the least suitable point with zero suitability or point d in Figure 5.39.



Multi-Criteria/Multi-Objective Decision Wizard

Objective 1: Site_selection

Specify factor standardization:

Factor number: 3
Input factor name: Tot_Sulfur
Minimum data value: 0.0000
Maximum data value: 8.0300

Factors to standardize with FUZZY
- Moisture
- Ash
- Tot_Sulfur
- Total_Carb
- Volatile_m
- BTU_Per_lb

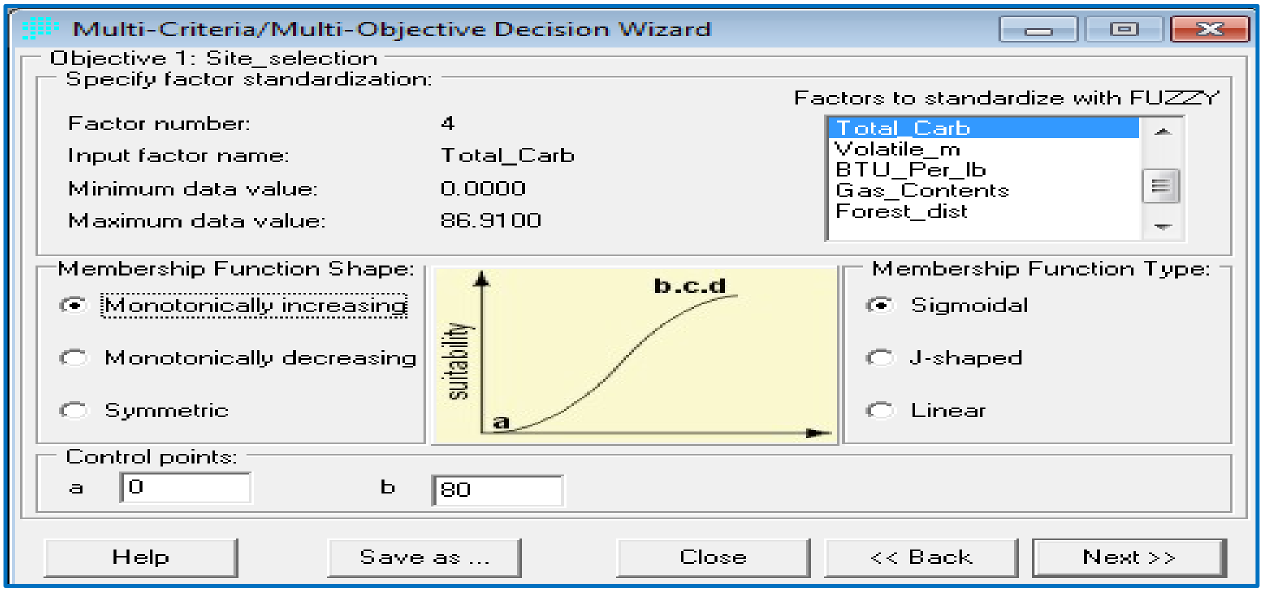
Membership Function Shape:
- ○ Monotonically increasing
- ● Monotonically decreasing
- ○ Symmetric

Membership Function Type:
- ● Sigmoidal
- ○ J-shaped
- ○ Linear

Control points:
c 5
d 8.03

Figure 5.39: Fuzzy rule for sulfur contents

For **carbon contents**, heating value in BTU/lb., gas contents and distance from forests, the monotonically increasing sigmoidal function was used because the suitability of the site increases with the increase in these factors. The more the heat, carbon and gas contents in the coal, the more that site is suitable for selection. Figures 5.40 to 5.43 show the fuzzy rules defined for these factors.



Multi-Criteria/Multi-Objective Decision Wizard

Objective 1: Site_selection

Specify factor standardization:

Factor number: 4
Input factor name: Total_Carb
Minimum data value: 0.0000
Maximum data value: 86.9100

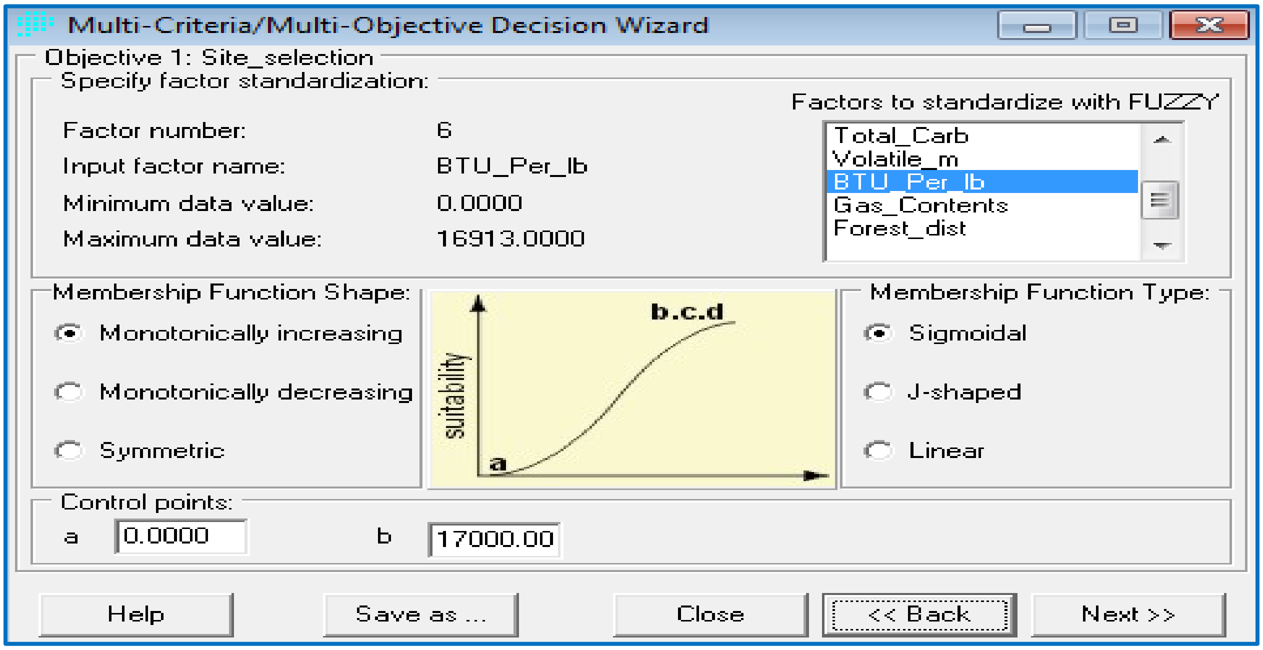
Factors to standardize with FUZZY
Total_Carb
Volatile_m
BTU_Per_lb
Gas_Contents
Forest_dist

Membership Function Shape:
● Monotonically increasing
○ Monotonically decreasing
○ Symmetric

Membership Function Type:
● Sigmoidal
○ J-shaped
○ Linear

Control points:
a 0
b 80

Figure 5.40: Fuzzy rule for carbon contents



Multi-Criteria/Multi-Objective Decision Wizard

Objective 1: Site_selection

Specify factor standardization:

Factor number: 6
Input factor name: BTU_Per_lb
Minimum data value: 0.0000
Maximum data value: 16913.0000

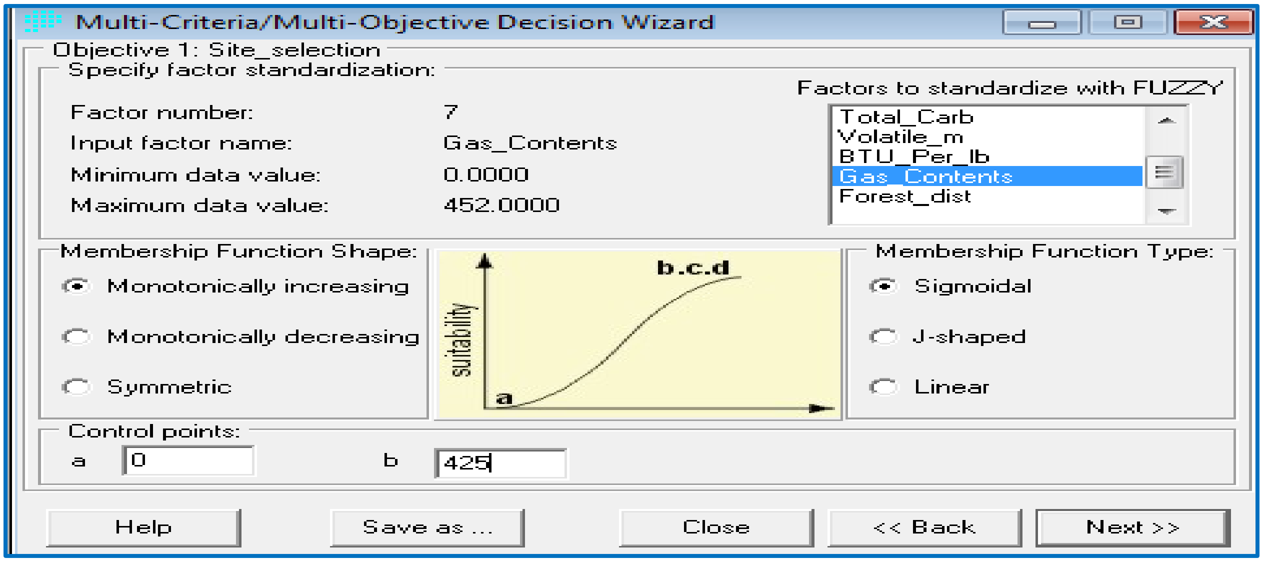
Factors to standardize with FUZZY
Total_Carb
Volatile_m
BTU_Per_lb
Gas_Contents
Forest_dist

Membership Function Shape:
● Monotonically increasing
○ Monotonically decreasing
○ Symmetric

Membership Function Type:
● Sigmoidal
○ J-shaped
○ Linear

Control points:
a 0.0000
b 17000.00

Figure 5.41: Fuzzy rule for heat contents



Multi-Criteria/Multi-Objective Decision Wizard

Objective 1: Site_selection

Specify factor standardization:

Factor number: 7

Input factor name: Gas_Contents

Minimum data value: 0.0000

Maximum data value: 452.0000

Factors to standardize with FUZZY

Total_Carb
Volatile_m
BTU_Per_lb
Gas_Contents
Forest_dist

Membership Function Shape:

● Monotonically increasing
○ Monotonically decreasing
○ Symmetric

Membership Function Type:

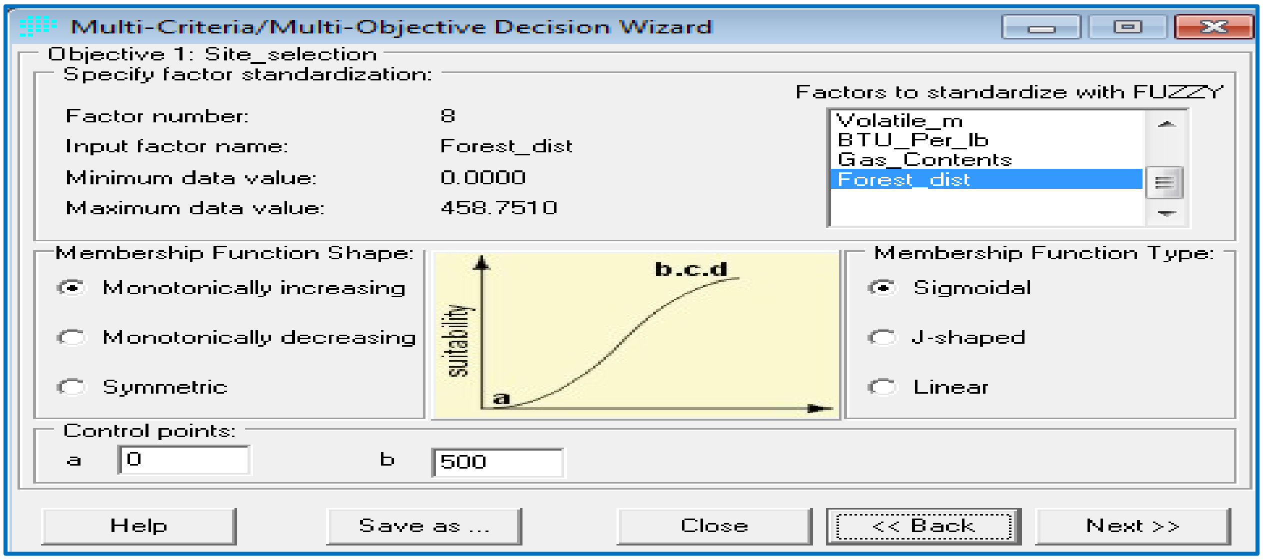
● Sigmoidal
○ J-shaped
○ Linear

Control points:

a 0

b 425

Figure 5.42: Fuzzy rule for gas contents



Multi-Criteria/Multi-Objective Decision Wizard

Objective 1: Site_selection

Specify factor standardization:

Factor number: 8

Input factor name: Forest_dist

Minimum data value: 0.0000

Maximum data value: 458.7510

Factors to standardize with FUZZY

Volatile_m
BTU_Per_lb
Gas_Contents
Forest_dist

Membership Function Shape:

● Monotonically increasing
○ Monotonically decreasing
○ Symmetric

Membership Function Type:

● Sigmoidal
○ J-shaped
○ Linear

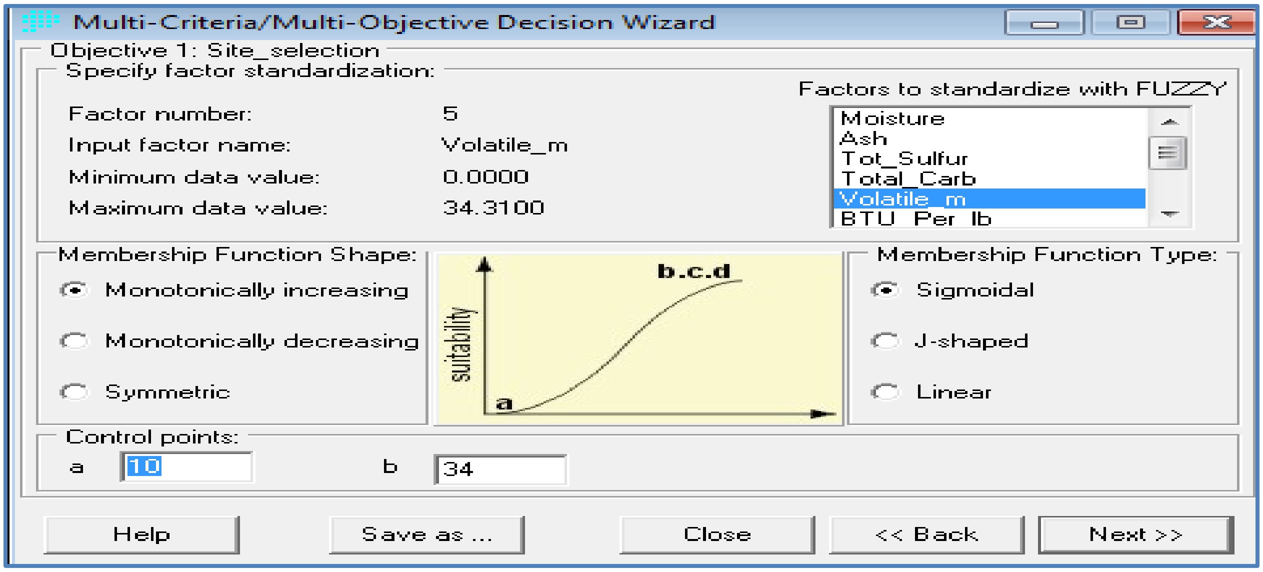
Control points:

a 0

b 500

Figure 5.43: Fuzzy rule for distance from forests

For **volatile matter,** the monotonically increasing sigmoidal function was used, as the decrease in the volatile matter decreases the suitability of coal for consideration in site selection. Figure 5.44 shows the image stating fuzzy rules for volatile matter. If the volatile matter is less than 10%, the coal is coking coal and not suitable for gasification. When the volatile matter reaches at 34%, the suitability levels off and does not increase further.



Objective 1: Site_selection
Specify factor standardization:

Factor number: 5
Input factor name: Volatile_m
Minimum data value: 0.0000
Maximum data value: 34.3100

Factors to standardize with FUZZY
Moisture
Ash
Tot_Sulfur
Total_Carb
Volatile_m
BTU_Per_lb

Membership Function Shape:
● Monotonically increasing
○ Monotonically decreasing
○ Symmetric

Membership Function Type:
● Sigmoidal
○ J-shaped
○ Linear

Control points:
a 10
b 34

Figure 5.44: Fuzzy rule for heat contents

Figures 5.45 to 5.52 show images after standardization through the fuzzy rules.

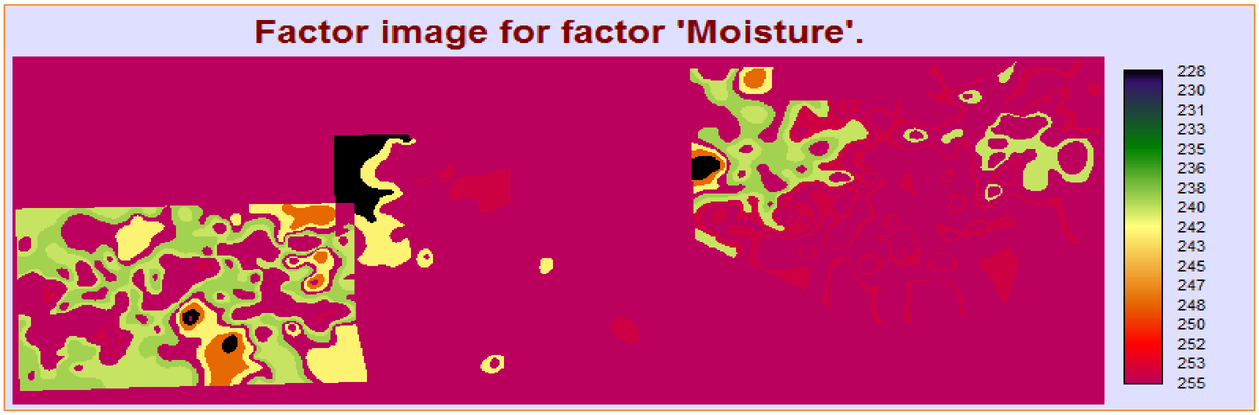


Figure 5.45: Image for moisture contents after standardization

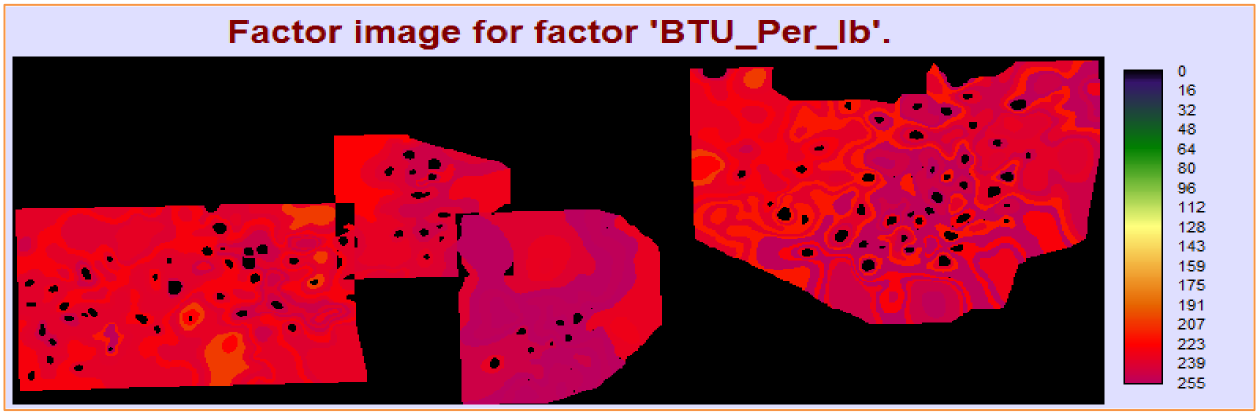


Figure 5.46: Heat contents after fuzzy standardization

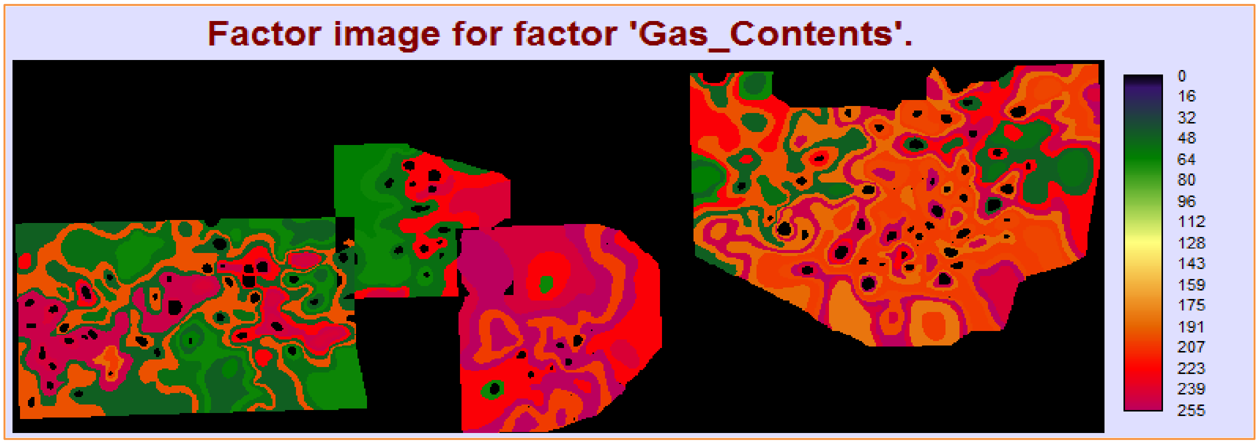


Figure 5.47: Gas contents image after fuzzy standardization

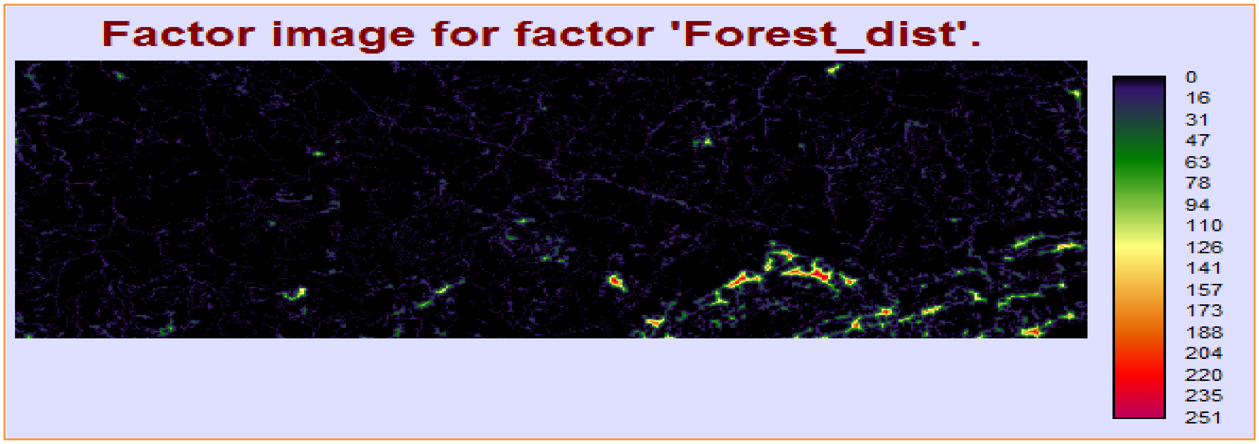


Figure 5.48: Standardized image for distances from forests

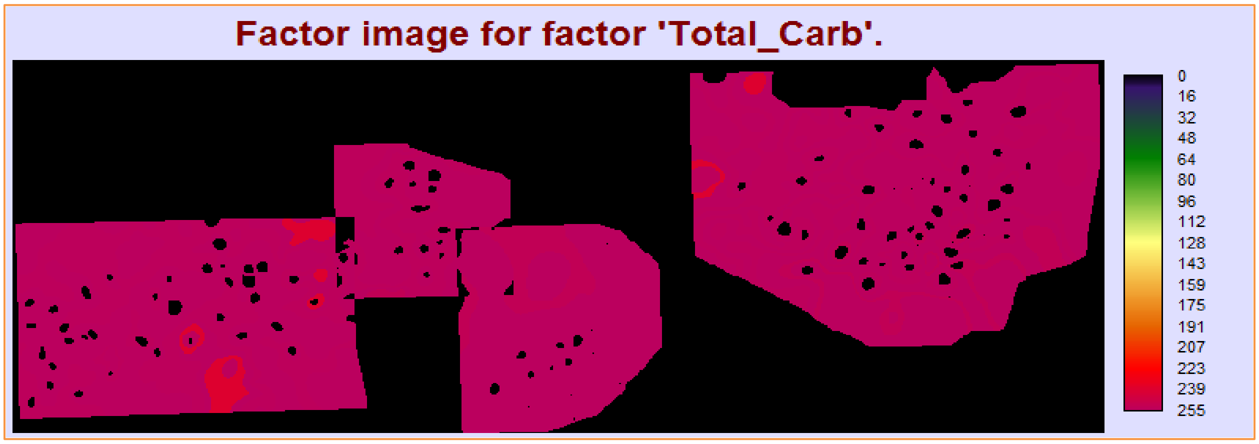


Figure 5.49: Carbon contents image after fuzzy standardization

Figure 5.50: Fuzzy standardization for ash contents

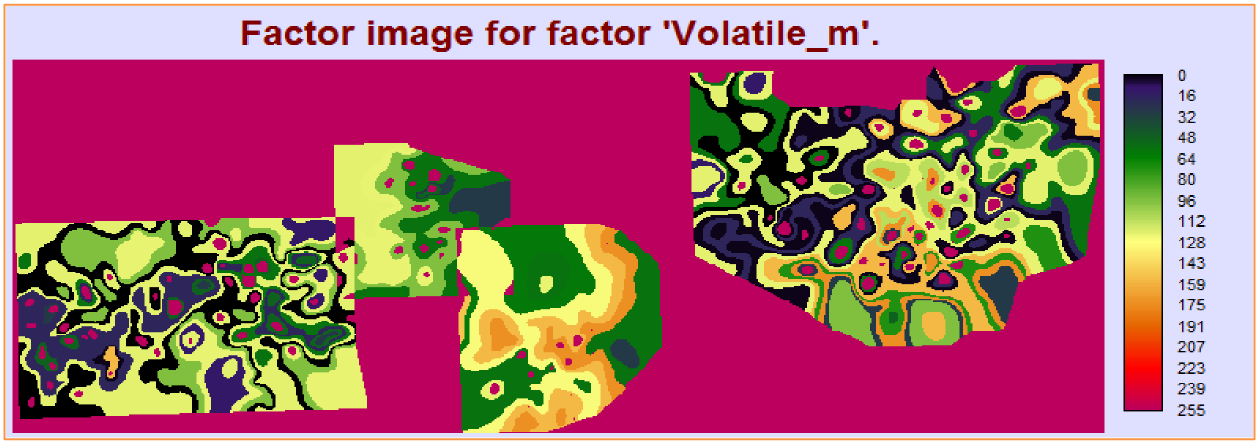


Figure 5.51: Fuzzy standardization for volatile matter

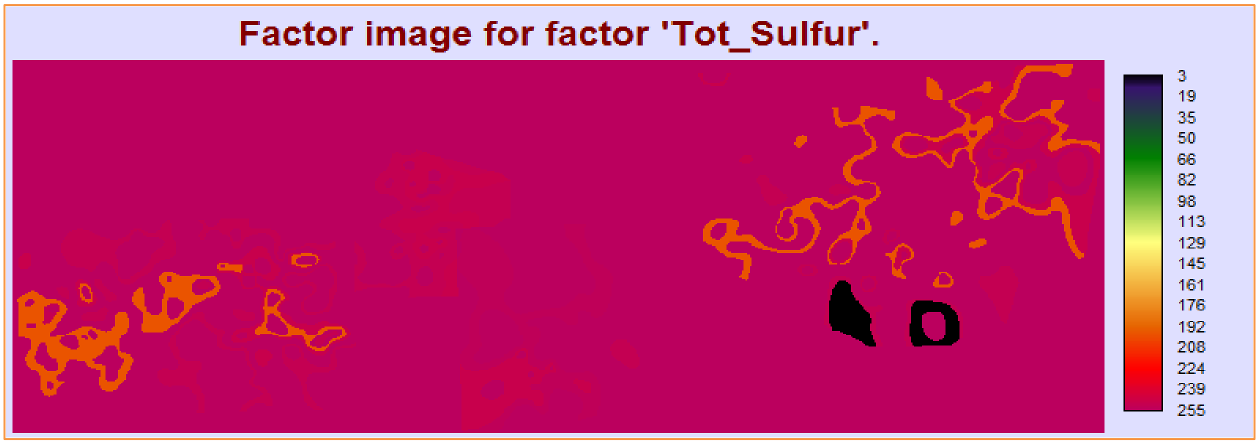
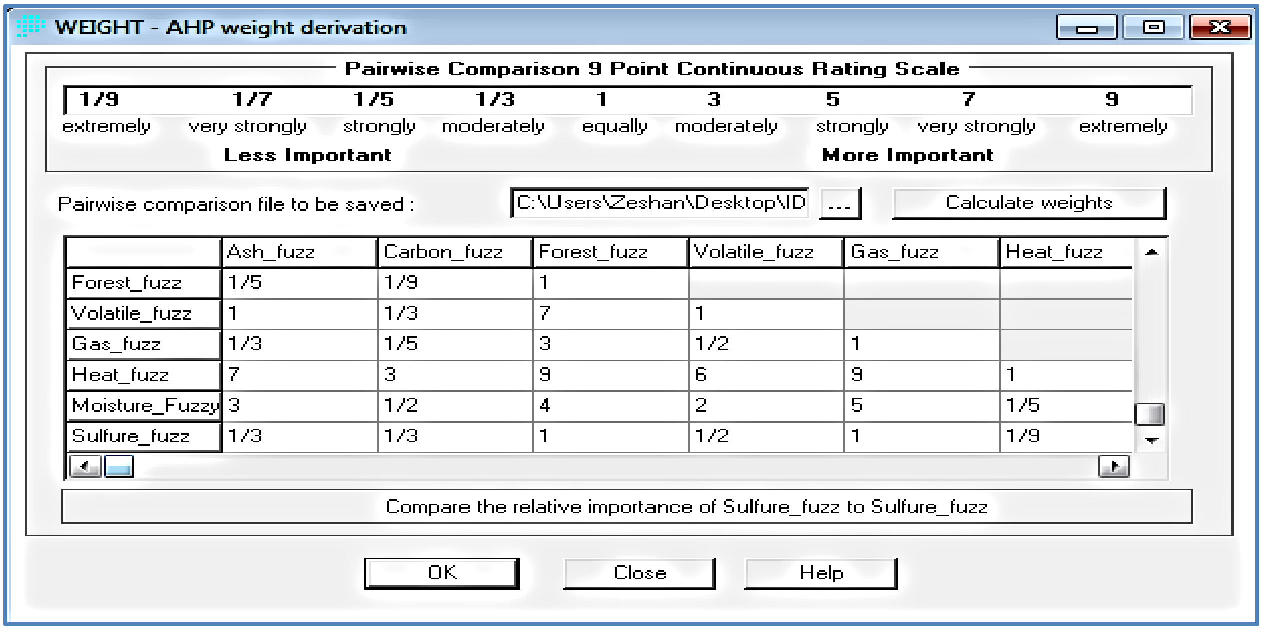


Figure 5.52: Fuzzy standardization for sulfur contents of coal

5.11.2 Weighting the factors

After standardization of factors, the next step was to assign weights to the factors. For this purpose, the analytical hierarchical process (AHP) was used where a pairwise comparison approach was applied to derive the factor weights. The pairwise comparison was based on a 9-point continuous rating scale, with "9" being extremely important relative to other factors and "1/9" extremely less important. The weights were then produced using the principal eigenvector of the pairwise comparison matrix. The module also generated a consistency index based on the computed weights by comparing one weight to the others. A consistency ratio less than 0.1 indicated acceptable weighting and if the consistency ratio was more than 0.1, then the rating of factors had to be re-evaluated until the best fit weightings were achieved, marked by a consistency ratio less than 0.1. Figures 5.53 and 5.54 show the pairwise comparison matrix and calculated weights and consistency ratio for this comparison. Carbon content and BTU/lb. have the highest weights whereas sulfur contents and distance from forest got the lowest weights. The consistency ratio for this comparison was 0.05. The module gave the control over the weighting procedure and provided the flexibility to assign the ranking to factors as desired by the planner or company.



Pairwise Comparison 9 Point Continuous Rating Scale

1/9	1/7	1/5	1/3	1	3	5	7	9
extremely	very strongly	strongly	moderately	equally	moderately	strongly	very strongly	extremely

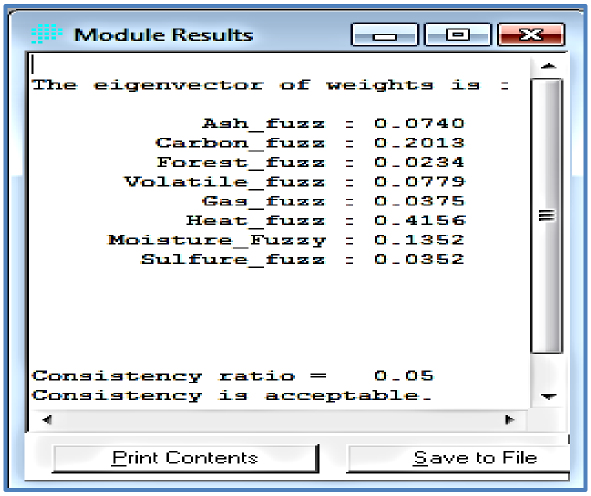
Less Important — More Important

Pairwise comparison file to be saved : C:\Users\Zeshan\Desktop\ID

	Ash_fuzz	Carbon_fuzz	Forest_fuzz	Volatile_fuzz	Gas_fuzz	Heat_fuzz
Forest_fuzz	1/5	1/9	1			
Volatile_fuzz	1	1/3	7	1		
Gas_fuzz	1/3	1/5	3	1/2	1	
Heat_fuzz	7	3	9	6	9	1
Moisture_Fuzzy	3	1/2	4	2	5	1/5
Sulfure_fuzz	1/3	1/3	1	1/2	1	1/9

Compare the relative importance of Sulfure_fuzz to Sulfure_fuzz

Figure 5.53: Pairwise comparison for factor weights

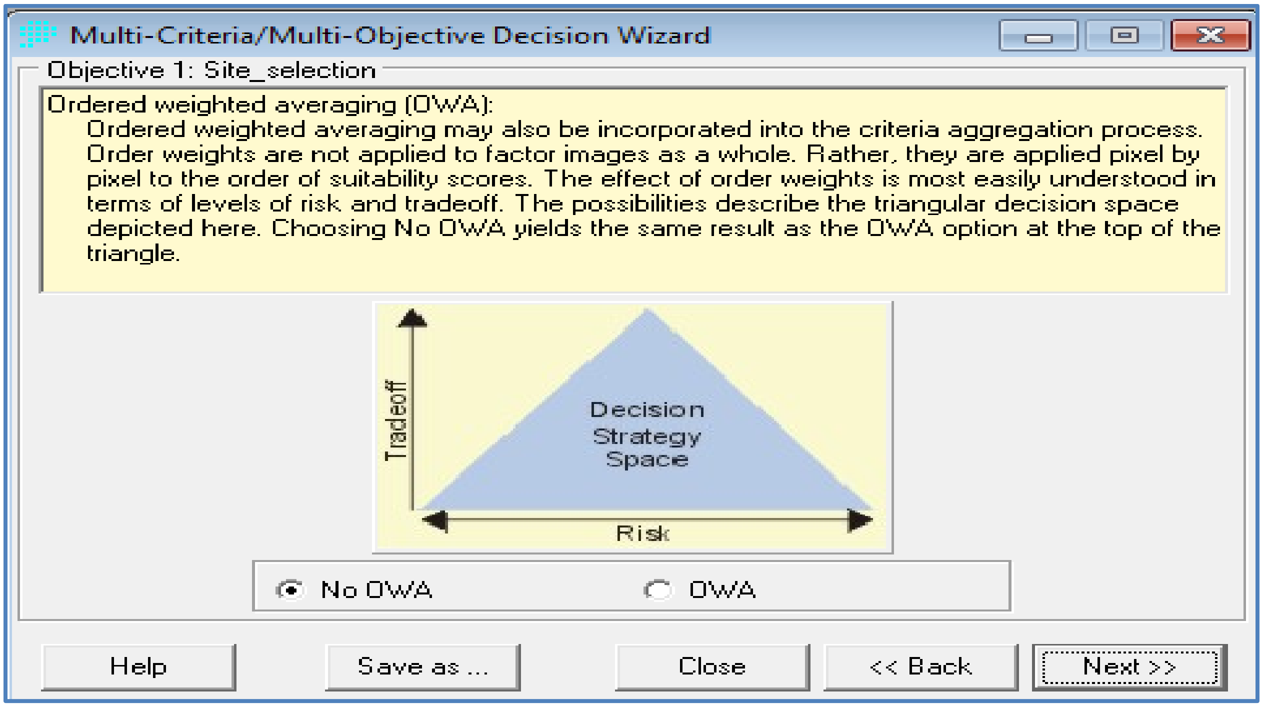


```
The eigenvector of weights is :

          Ash_fuzz : 0.0740
       Carbon_fuzz : 0.2013
       Forest_fuzz : 0.0234
     Volatile_fuzz : 0.0779
          Gas_fuzz : 0.0375
         Heat_fuzz : 0.4156
    Moisture_Fuzzy : 0.1352
      Sulfure_fuzz : 0.0352




Consistency ratio =   0.05
Consistency is acceptable.
```

Figure 5.54: Weights calculated after pairwise comparison

5.11.3 <u>Ordered Weighted Average (OWA)</u>

For OWA, no OWA option was used as full tradeoff between factors was required. No OWA is similar to the top of triangle with OWA weights and yields full tradeoff at average risk. Figure 5.55 shows the OWA triangle and no weighting scheme for these factors.



Ordered weighted averaging (OWA):

Ordered weighted averaging may also be incorporated into the criteria aggregation process. Order weights are not applied to factor images as a whole. Rather, they are applied pixel by pixel to the order of suitability scores. The effect of order weights is most easily understood in terms of levels of risk and tradeoff. The possibilities describe the triangular decision space depicted here. Choosing No OWA yields the same result as the OWA option at the top of the triangle.

● No OWA ○ OWA

Figure 5.55: No OWA weights for these factors

Figure 5.56 shows the final image after running through the whole process. It shows that highest suitability ranking for a site is 247 whereas lowest suitable site has a ranking of 82 after combination of factors that can tradeoff.

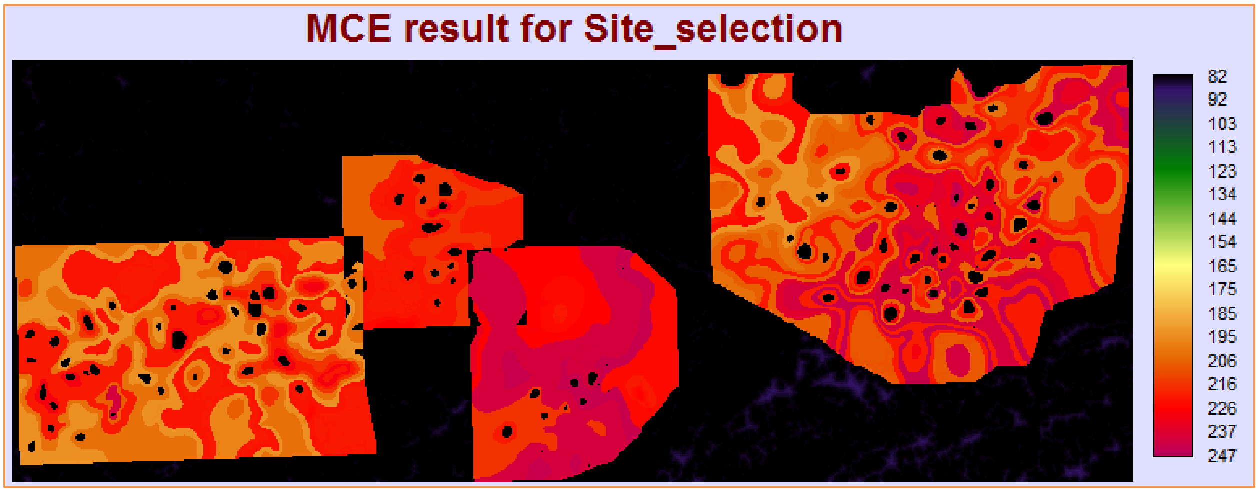
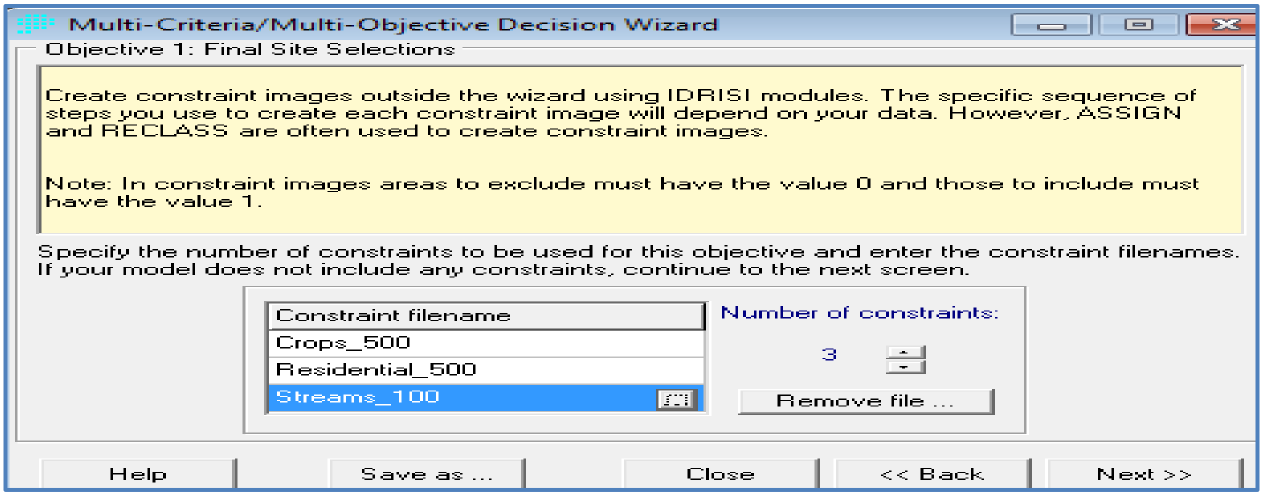


Figure 5.56: Final image after processing factors that tradeoff

5.12 Modeling for Constraints and Factors that do not Tradeoff

The next step was to process this newly created factor image, the factors that do not tradeoff and the constraints. The constraints used for this model were crop/agricultural land, residential areas and major water bodies. The constraints were set in such a way that the areas around 100 m of major water bodies and 500 m of crops/agricultural lands and developed areas were not considered for site selection. Thus, a buffer distance of 100 m around major water bodies and 500 m around crops and residential areas was created and a value of '1' was assigned to the areas beyond that buffer zone and '0' for the areas within the buffer zone. Any factors or scores within the buffer zone would multiply with zero and be automatically declared as unsuitable for selection. Figure 5.57 shows the constraint set for processing.


Multi-Criteria/Multi-Objective Decision Wizard

Objective 1: Final Site Selections

Create constraint images outside the wizard using IDRISI modules. The specific sequence of steps you use to create each constraint image will depend on your data. However, ASSIGN and RECLASS are often used to create constraint images.

Note: In constraint images areas to exclude must have the value 0 and those to include must have the value 1.

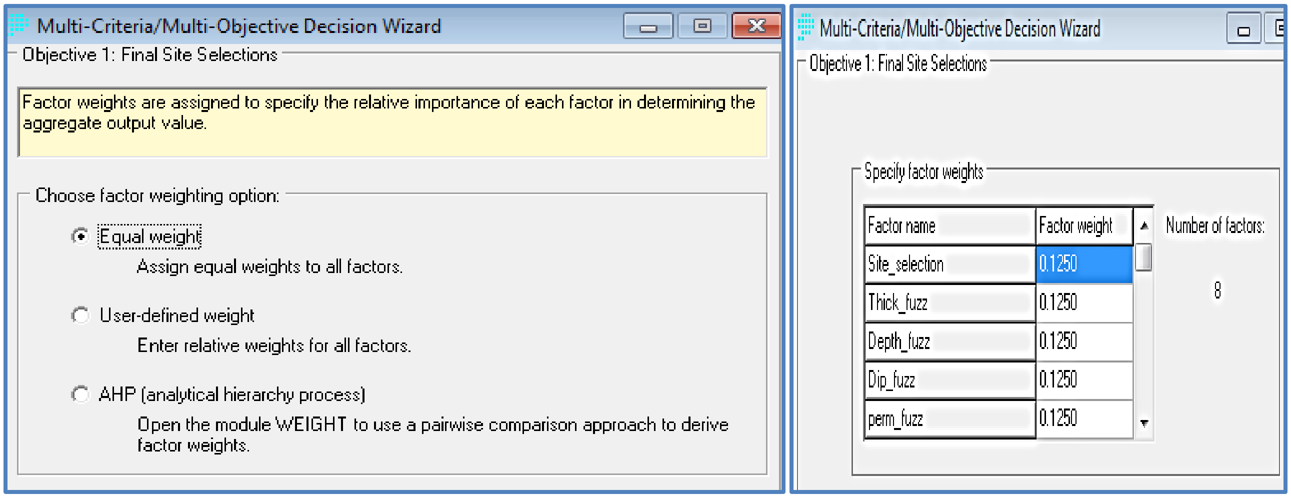
Specify the number of constraints to be used for this objective and enter the constraint filenames. If your model does not include any constraints, continue to the next screen.

Constraint filename
Crops_500
Residential_500
Streams_100

Number of constraints: 3

Figure 5.57: Three constraints used for model

For these factors, equal weights were assigned so that they did not tradeoff. The OWA weights were assigned later to determine the amount of risk in the results. The procedure was similar to the one explained earlier in the chapter with the exception that equal factor weights were given to all factors and later on OWA weights were assigned to determine the amount of risk. Figure 5.58 shows the equal weights assigned to these factors.


Multi-Criteria/Multi-Objective Decision Wizard

Objective 1: Final Site Selections

Factor weights are assigned to specify the relative importance of each factor in determining the aggregate output value.

Choose factor weighting option:

● Equal weight
Assign equal weights to all factors.

○ User-defined weight
Enter relative weights for all factors.

○ AHP (analytical hierarchy process)
Open the module WEIGHT to use a pairwise comparison approach to derive factor weights.

Multi-Criteria/Multi-Objective Decision Wizard

Objective 1: Final Site Selections

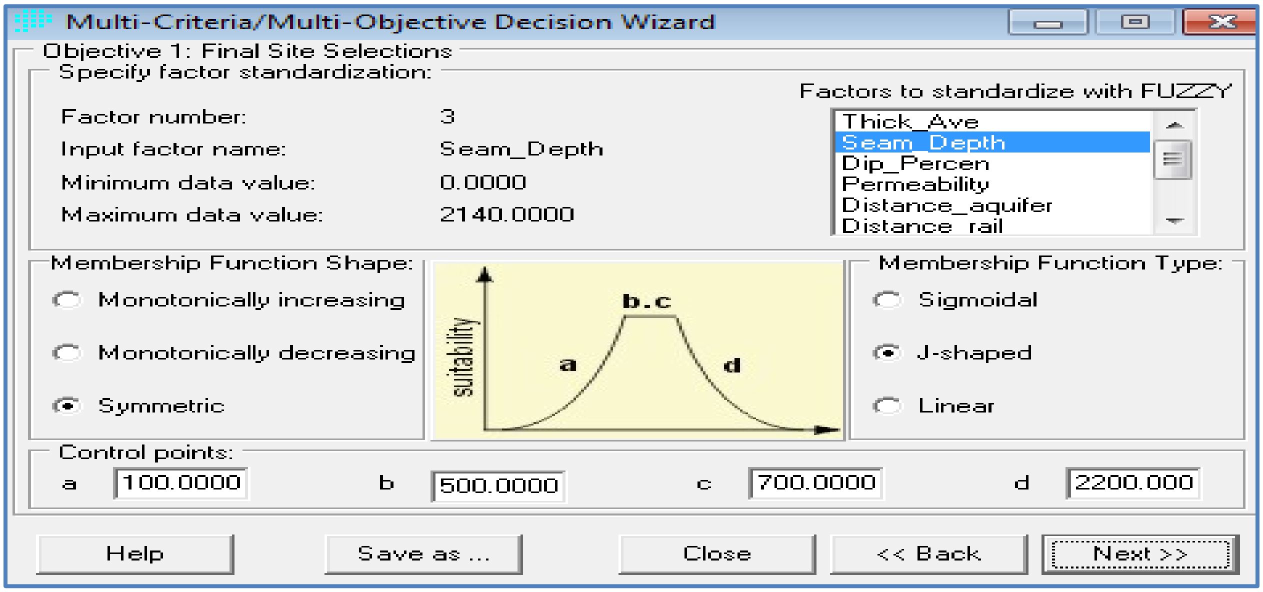
Specify factor weights

Factor name	Factor weight
Site_selection	0.1250
Thick_fuzz	0.1250
Depth_fuzz	0.1250
Dip_fuzz	0.1250
perm_fuzz	0.1250

Number of factors: 8

Figure 5.58: Equal weights assigned to factors

Coal seam thickness, seam dip, coal rank, depth, permeability, distance from roads, railways and aquifers were factors and major water bodies, residential areas and crop areas were constraints. For standardization of these factors, fuzzy rules were used except for the factor resulting from combination of factors that tradeoff, as it was already standardized in the previous step. For distance from roads and rails, the monotonically decreasing sigmoidal function was used, as the farther the distance from these features, the lesser the suitability of the sites. For coal rank, dip, permeability and distance from aquifer, the monotonically increasing sigmoidal function was used, as the higher the values of these features, the more suitable the site for selection. For coal seam depth, the J-shaped symmetrical function was used because very shallow and very deep seams make the site unsuitable. At shallower depths, the subsidence and gas leakage is pronounced whereas at higher depths drilling cost and pressure maintenance requirements increase significantly. Thus, a seam 150 to 500 m deep is considered most suitable. Figure 5.59 shows the fuzzy rules defined for depth. The suitability increases from 100 m to 500 m (points a & b), levels off until 700 m and then declines (points c & d).



Multi-Criteria/Multi-Objective Decision Wizard

Objective 1: Final Site Selections

Specify factor standardization:

Factor number: 3
Input factor name: Seam_Depth
Minimum data value: 0.0000
Maximum data value: 2140.0000

Factors to standardize with FUZZY
- Thick_Ave
- Seam_Depth
- Dip_Percen
- Permeability
- Distance_aquifer
- Distance_rail

Membership Function Shape:
- ○ Monotonically increasing
- ○ Monotonically decreasing
- ● Symmetric

Membership Function Type:
- ○ Sigmoidal
- ● J-shaped
- ○ Linear

Control points:
a 100.0000
b 500.0000
c 700.0000
d 2200.000

Figure 5.59: J-shaped symmetrical function for standardization of depths

5.13 Ordered Weighted Average (OWA) and Risk Assessment

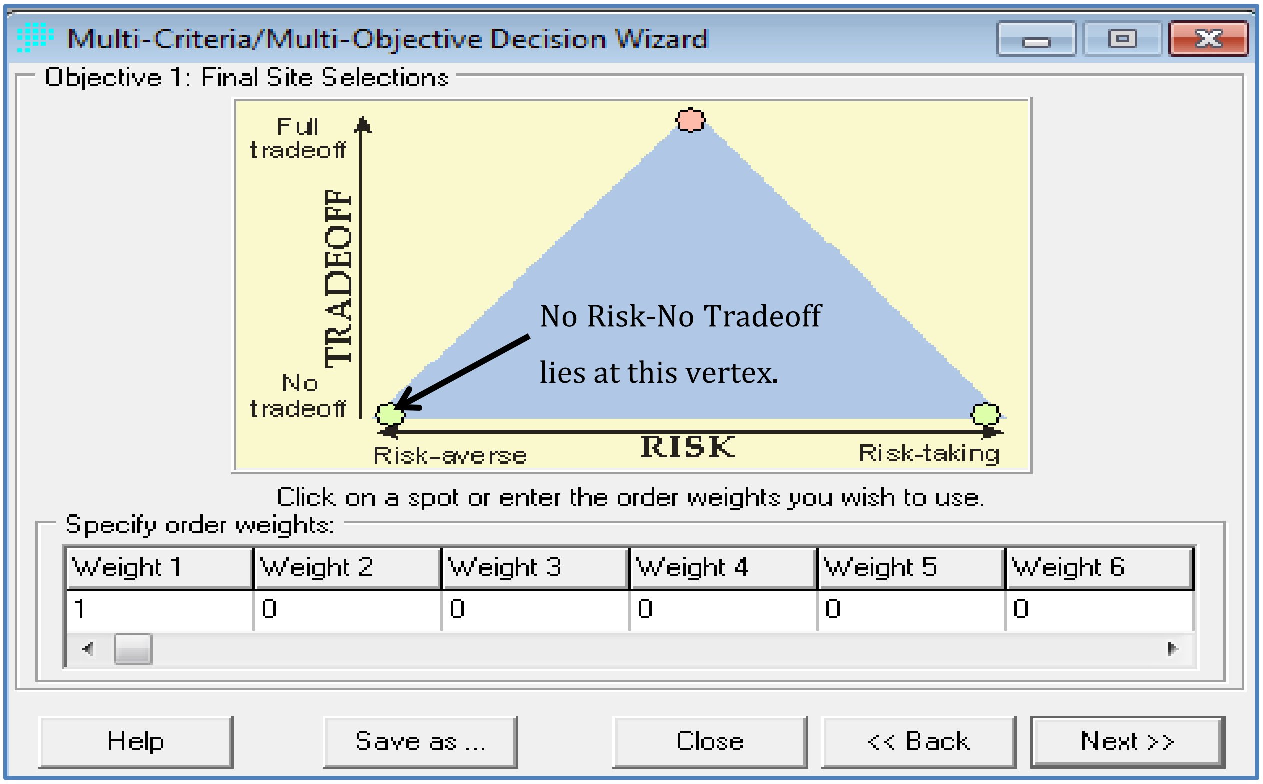
After standardization and weighting of factors, the next step was to define OWA weights for the factors. The OWA weights determine the amount of risk and level of tradeoff allowed between factors. They give control over factors by applying a second weight to factors. For this model, the following four cases for OWA were considered, though several other scenarios could be generated based on OWA weightings.

i. Least Risk-No Tradeoff (AND overlay)

ii. Full Risk-No Tradeoff (OR overlay)
iii. Average Risk-No Tradeoff
iv. Average Risk-Full Trade off

5.13.1 <u>No/Least Risk-No Tradeoff</u>

In this case, the smallest value gets all the weight and eliminates any tradeoff between factors. The locations are controlled by factors of minimum suitability and there is no compensation for deficiencies in factors, as no tradeoff is allowed. It is similar to extreme left vertex of OWA triangle and is an 'AND' operation. All the conditions must be met for a site to be considered suitable. Its weighting matrix is [1 0 0 0 0 0 0 0]. Figure 5.60 shows the no-risk-no tradeoff case.



Objective 1: Final Site Selections

No Risk-No Tradeoff

lies at this vertex.

Click on a spot or enter the order weights you wish to use.

Specify order weights:

Weight 1	Weight 2	Weight 3	Weight 4	Weight 5	Weight 6
1	0	0	0	0	0

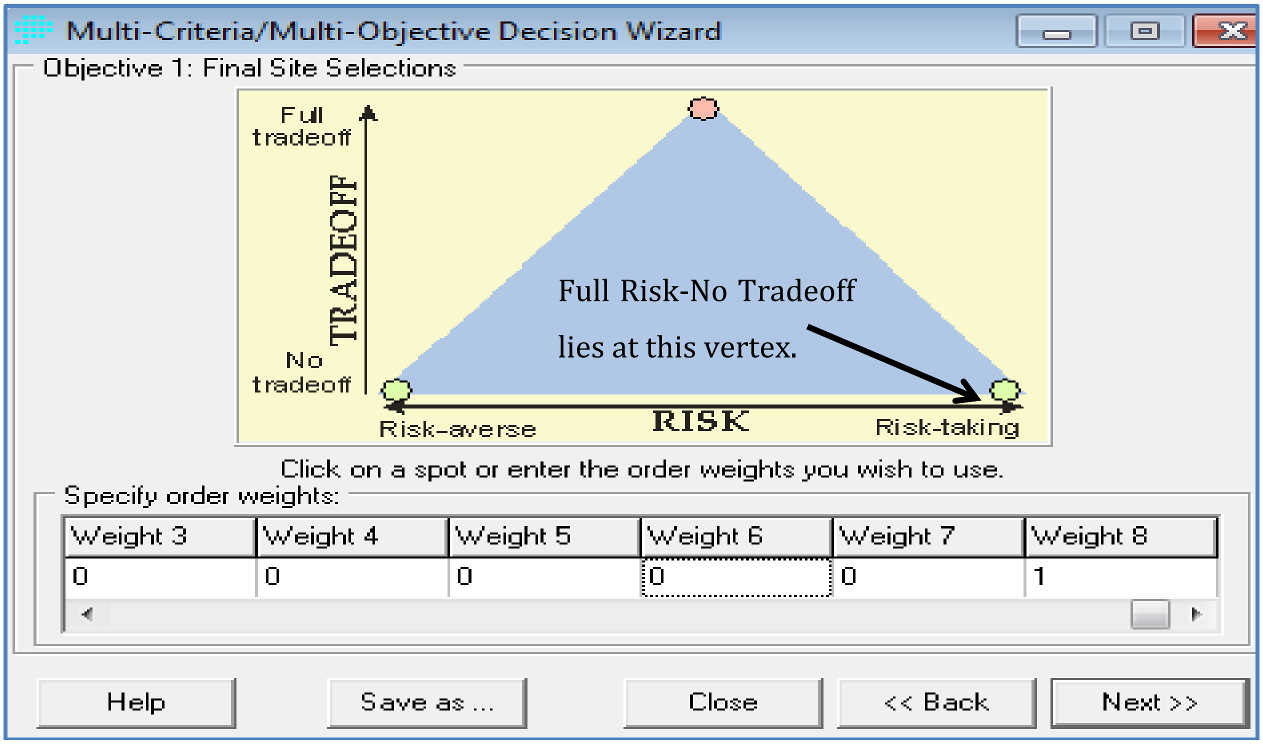
Figure 5.60: No risk-no-tradeoff OWA weighting

Figure 5.61 shows the sites for no risk-no tradeoff case. The highest suitability ranking for this image is only 32. Although it has eliminated the risk of making any wrong decision, the options however are very limited.

Figure 5.61: Suitability image for sites with no risk no tradeoff scenario

5.13.2 <u>Full Risk-No Tradeoff</u>

In this case, the highest weighting factor decides the location suitability and no tradeoff between factors are allowed. It is similar to the extreme right vertex of the OWA triangle and similar to 'OR' operation. Meeting any single criterion will put the site in the suitability list, hence most risky scenario. The weighting matrix is [0 0 0 0 0 0 0 1]. Figure 5.62 shows the OWA weighting for this scenario.



Full Risk-No Tradeoff lies at this vertex.

Weight 3	Weight 4	Weight 5	Weight 6	Weight 7	Weight 8
0	0	0	0	0	1

Figure 5.62: Full risk-no-tradeoff OWA weighting

The highest suitability ranking for the resulting sites is 255 and only the sites that are eliminated by constraints are not included in the suitability list. Since any one factor can put the site in the suitability list, the probability of making the wrong decision is very high. Figure 5.63 shows the resulting image for this scenario.

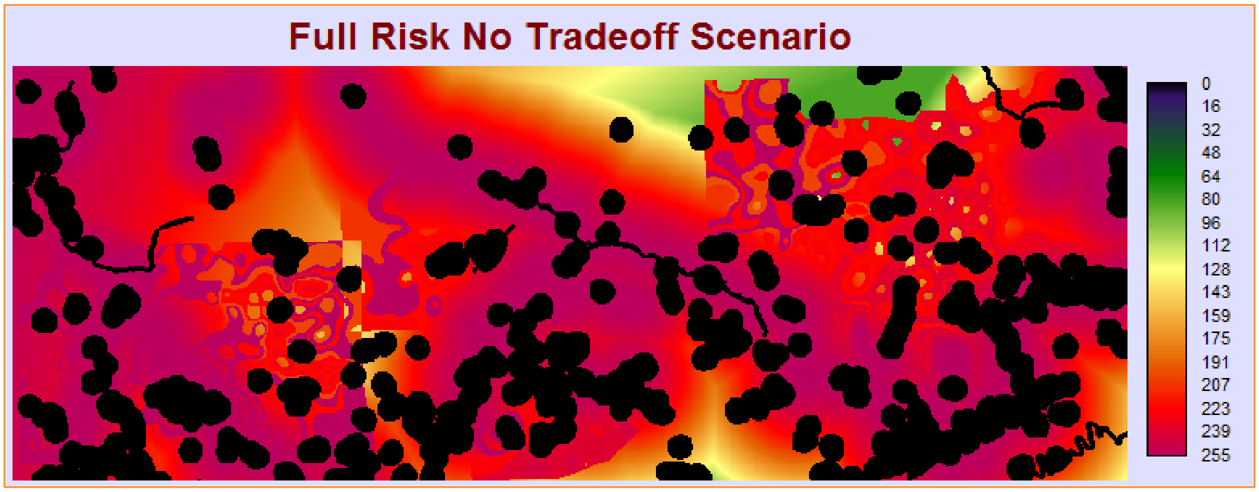
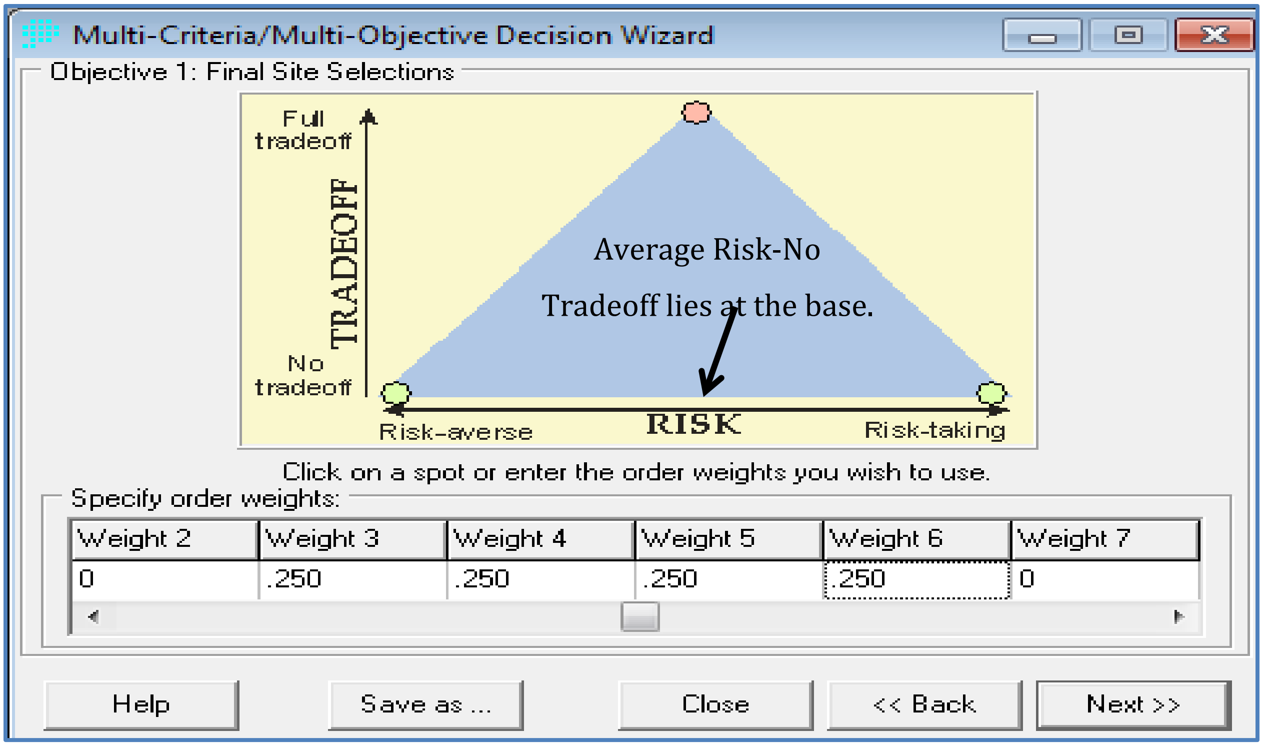


Figure 5.63: Suitability image for sites with full risk no tradeoff scenario

5.13.3 Average Risk-No Tradeoff

In this scenario, the central values decide the suitability of location and extreme values are not weighted. The risk is average and there is still no tradeoff between factors. The location is at the base of the triangle in the center. The weight matrix is [0 0 0.250 0.250 0.250 0.250 0 0]. Figure 5.64 shows the weightings for this case.



Objective 1: Final Site Selections

Click on a spot or enter the order weights you wish to use.

Specify order weights:

Weight 2	Weight 3	Weight 4	Weight 5	Weight 6	Weight 7
0	.250	.250	.250	.250	0

Figure 5.64: Average risk-no-tradeoff OWA weighting

The highest suitability ranking for resulting sites is 206. There is average risk of making the wrong decision and there is a range of options available for selection. Figure 5.65 shows the resulting raster image.

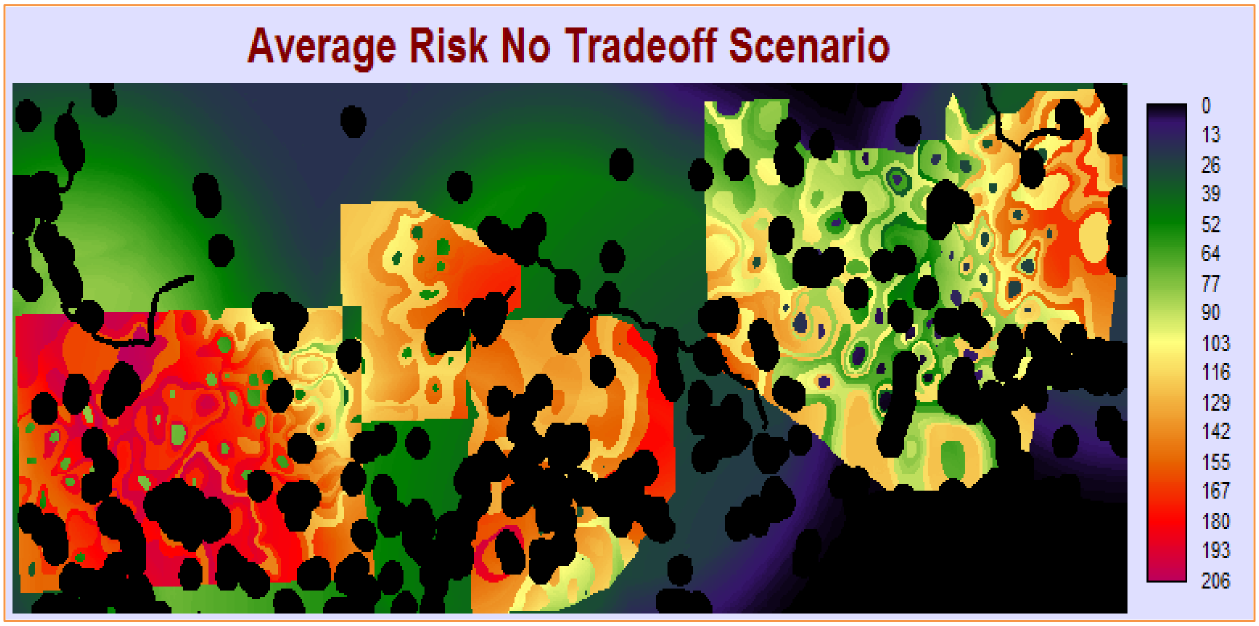
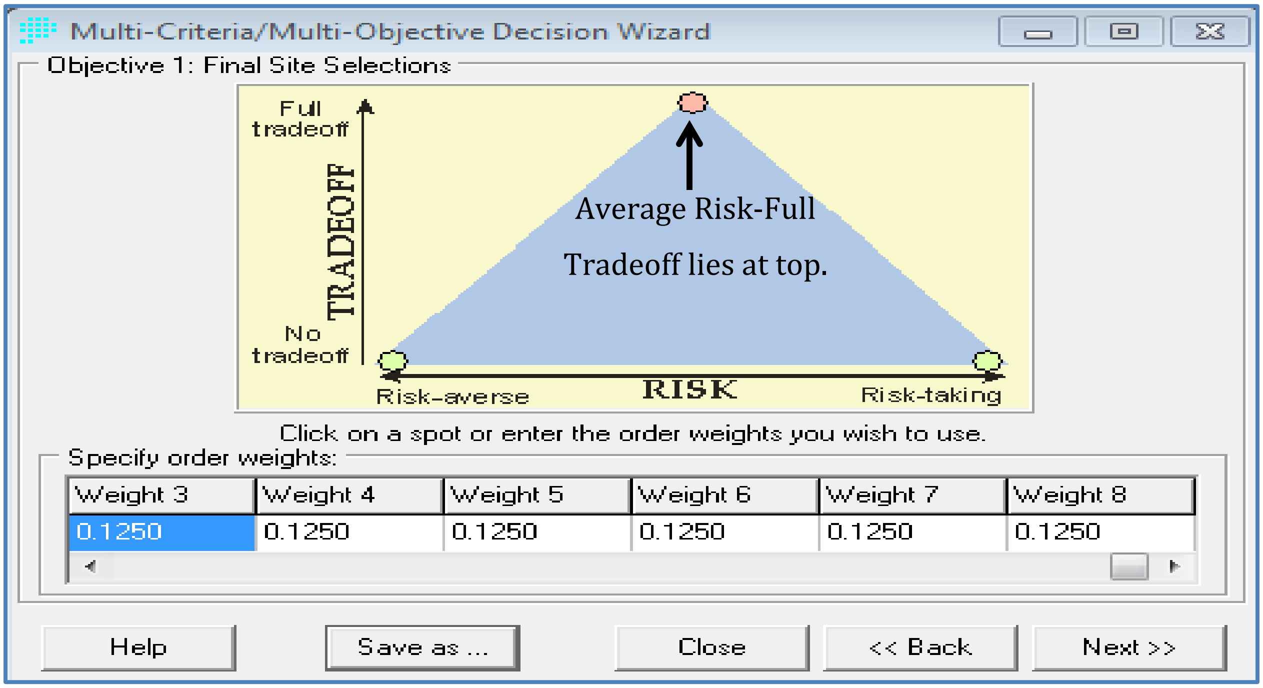


Figure 5.65: Suitability image for average risk no tradeoff scenario

5.13.4 Average Risk-Full Tradeoff

In this scenario, all factors are equally weighted at OWA stage and there is full tradeoff between highest valued and lowest valued factors. The risk is average and the location is at the top of triangle as shown in Figure 5.66 . Extreme valued as well as central factors decide the suitability of sites. The weighting matrix for these factors is [0.125 0.125 0.125 0.125 0.125 0.125 0.125 0.125].



Click on a spot or enter the order weights you wish to use.

Specify order weights:

Weight 3	Weight 4	Weight 5	Weight 6	Weight 7	Weight 8
0.1250	0.1250	0.1250	0.1250	0.1250	0.1250

Figure 5.66: Average risk-full-tradeoff OWA weighting

The highest suitability ranking for this image is 177 and the factors do tradeoff. The scenario gives average risk in making wrong decision. The resulting image is shown in Figure 5.67.

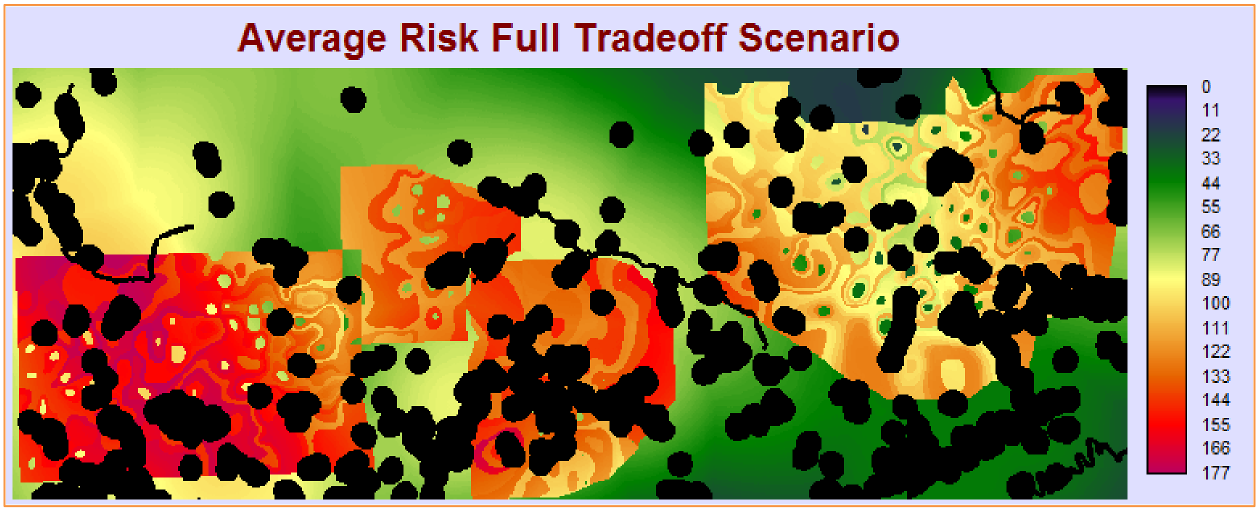


Figure 5.67: Suitability image Average risk full tradeoff scenario

5.14 Decision Hardening

After producing the suitability images and risk levels for the entire area, the final step was to harden the decision based on further conditions and constraints. This final step was the actual selection of most suitable areas from the ranked images by imposing more conditions. The procedure is the same for any image generated by the decision wizard. For example for this model, the area of interest was based on the suitability image of *average risk-no trade off* with suitability index lying between 150 and 206. The top 15-20 highest-ranking areas would be selected for final consideration.

For this step, the "Reclass" command was used to exclude the areas having a suitability index less than 150. Then the "Extract" command was used with the study area image as a feature definition image, to get the details of areas falling within the range of 150-206 suitability indexes. The resulting image is shown in Figure 5.68.

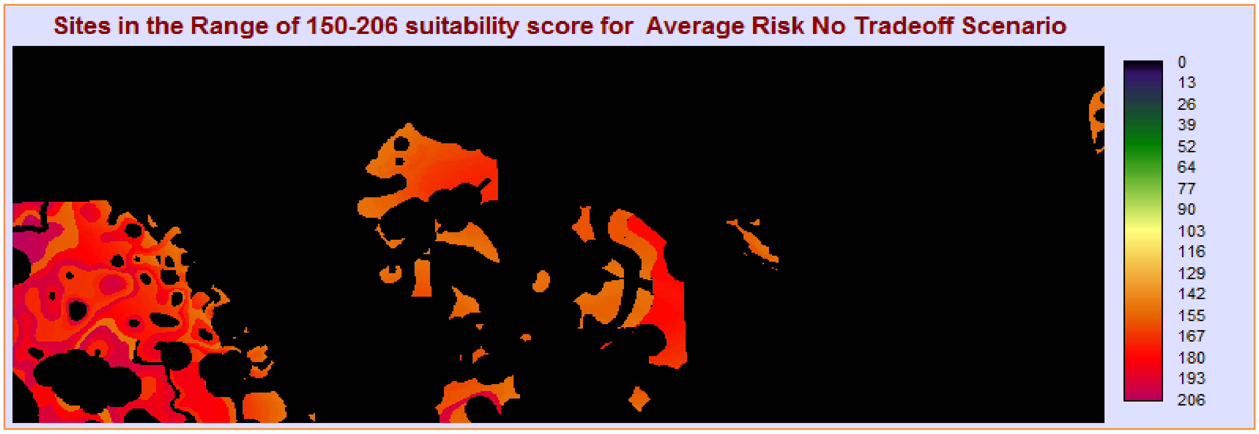
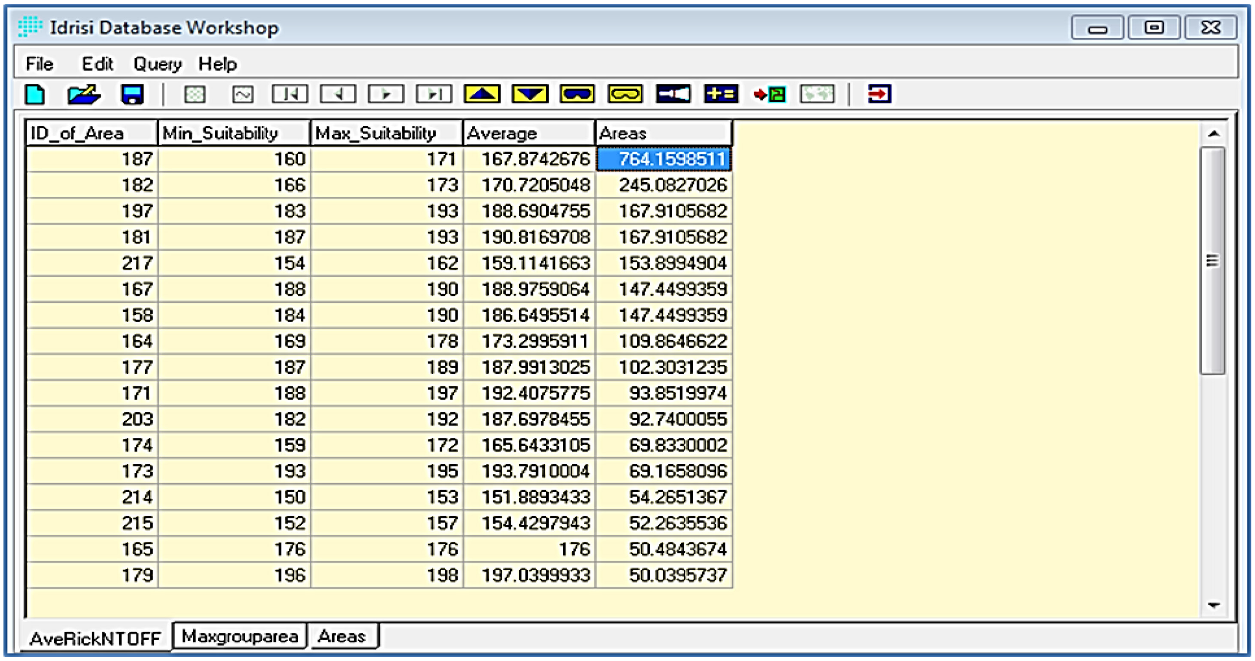


Figure 5.68: Image after reclassification for sites in the suitability range of 150-206

Database query was run to get the highest-ranking areas in this range. The highest-ranking area had a maximum suitability index of 198 and a minimum of 198 whereas second highest had a score of 195 and 193. Table 5.1 shows 17 areas that had a minimum ranking greater than 150. The area of the highest suitable site was about 50 acres and for second highly suitable site, it was about 70 acres. The site having the largest area of about 765 acres had a suitability score of 171 and the second largest site having an area of 245 acres had maximum suitability of 173. The areas can be increased by relaxing the constraint on suitability range and vice versa.

Table 5.1: Highest-ranking areas in the suitability range of 150-206



ID_of_Area	Min_Suitability	Max_Suitability	Average	Areas
187	160	171	167.8742676	764.1598511
182	166	173	170.7205048	245.0827026
197	183	193	188.6904755	167.9105682
181	187	193	190.8169708	167.9105682
217	154	162	159.1141663	153.8994904
167	188	190	188.9759064	147.4499359
158	184	190	186.6495514	147.4499359
164	169	178	173.2995911	109.8646622
177	187	189	187.9913025	102.3031235
171	188	197	192.4075775	93.8519974
203	182	192	187.6978455	92.7400055
174	159	172	165.6433105	69.8330002
173	193	195	193.7910004	69.1658096
214	150	153	151.8893433	54.2651367
215	152	157	154.4297943	52.2635536
165	176	176	176	50.4843674
179	196	198	197.0399933	50.0395737

The final image of the group of areas that are top candidates for selection is shown below. This data was based on polygons of the areas and limited to selected regions of Appalachia. When planning at regional-scale levels, e.g. for the entire basin or entire state, the zip codes, census tracts or larger area polygons would be more appropriate for modeling and site analysis.

Figure 5.69: Top-ranking sites for selection

5.15 Chapter Conclusions

This model gives a tool to select suitable sites for selection based on predefined criteria for selection. It helps in ranking the sites based on their suitability and level of risks involved in decision-making. The model gives a great flexibility in weighting the factors as per their importance in the defined criteria, establishing the constraints based on restrictions (legal, environmental, regulatory etc.) and finally selecting the levels of risk in the final decision. This model is not site specific and procedures described here can be applied to any site provided the data is available for that site. The model though applied to UCG, is applicable to any case where a suitable site is to be selected based on a defined criteria or rules.

Chapter 6 – Sustainability Assessment of UCG

6.1 Introduction[1]

UCG is attracting considerable global attention as a viable process to provide a "clean" and economic fuel from coal. Applying improved UICG technology to gasify deep, thin, and low-grade coal seams could vastly increase the amount of exploitable reserves. However, it is imperative that further development of this technology is based on integrating UCG practices and potential environmental impacts with accepted sustainability frameworks and processes. This chapter evaluates the potential of UCG to conform to frameworks such as MMSD (Mining, Minerals and Sustainable Development), Natural Step and Green Engineering, in order to define its "sustainable" potential. The chapter also discusses the potential contributions of UCG to sustainability during its design, operation, closure, and post-closure phases. The potential economic and environmental benefits and associated hazards of UCG necessitate that this technology is developed in line with sustainable development principles and UCG projects should conform to different accepted and recognized frameworks used to assess whether a project can be labeled as "sustainable".

6.2 Sustainability and Sustainable Development

Sustainability and sustainable development are different concepts and it is a misunderstanding to use them interchangeably. Sustainability is the ability of the system to withstand external shocks and pressures from social, environmental and economic needs and return to normal functioning after enduring these shocks [Shield, Solar et al. 2006]. Keeping in view the exhaustible nature of mineral resources and environmental implications of mining, some consider it an oxymoron to use the term mining sustainability

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[1] This chapter is based on the following paper: Hyder, Z., Karmis, M., *Assessing the Contribution of Underground In-Situ Coal Gasification (UICG) within a Sustainable Development Framework*, Aachen International Mining Symposia, 5th International Conference, "Sustainable Development in the Minerals Industry, SDIMI 2011" June 14-17, 2011 Aachen Germany, Pages 569-579.
The text is modified and formatted to fit the dissertation format.

[Van Zyl and Gagne 2010]. On the other hand, the concept of sustainable future development includes mining and mineral resources as integral part, necessitating strategies to develop these resources by integrate environmental concerns, economic development, social integrity and effective governance [Shield, Solar et al. 2006].

Sustainability assessment varies from case to case and involves multiple factors, site-specific characteristics and layers of uncertainty. As there are no clearly defined and mutually agreed criteria, the assessment exercise is not a precise process [Gibson, Hasan et al. 2005]. Like environmental assessment, sustainability assessment focuses on process and depends mainly on designing assessment regimes and decision-making strategies, however, its scope is broader than environmental assessment [Gibson, Hasan et al. 2005].

Thus to overcome these hurdles in assessment processes, several frameworks have been developed to facilitate development, assessment and measurement of strategies that enable sustainable development. While there is no ideal system, a number of accepted frameworks can be used as starting points for measurement and planning of sustainability. This chapter will focus on some of these frameworks and examine their applicability to the UCG technology.

6.3 Mining, Minerals and Sustainable Development

The main objective of the Mining, Minerals and Sustainable Development (MMSD), launched in 1999, was to assess and facilitate the transition of the mining and minerals sector toward a more sustainable future [IISD. 2002]. Under Task 2, the MMSD developed criteria for assessing the contribution of any project, including mining and minerals projects, towards sustainability. A framework was developed to assess whether or not a project has a net positive contribution towards sustainability. This framework is composed of seven parts, each in the form of a question that must be answered for the specific project and conditions [IISD. 2002].

The following discussion presents the seven questions, objectives, and their correspondence to a generalized UCG process. Indicators, examples and matrices that are more specific can be developed for particular sites of interest based on this framework.

6.3.1 MMSD Question 1 - Engagement

Are engagement processes in place and working effectively?

6.3.1.1 Objectives

Stake holders identification and engagement, dispute resolution mechanisms, adequate resources, reporting and verification [IISD. 2002]

6.3.1.2 UCG Conformity

Major stakeholders in UCG include investors, surface right holders, leaseholders, the surrounding community, federal and state departments, workers, product end users (e.g., power generation plants and consumers) and other people affected directly or indirectly by the project. The idea of stakeholder mapping is to recognize each having conflicting interests in the projects and to develop a strategy for conflict resolution by including all the stakeholders in the decision making process at various stages of project. This may give rise to a project development that is welcomed by at least a majority of stakeholders. In case of UCG, the potential conflict may be between the coal or coalbed methane leaseholder and the UCG Company. However, since potential UCG sites are abandoned mines, low quality uneconomic coal and deep seated, steeply dipping coal seams [Lamb 1977], the chances of dispute are minimized. Secondly, due to minimal disruption at the surface and minimized land acquisition and rehabilitation requirements [Ghose and Paul 2007], the stakeholder disagreements concerning surface rights and surface reclamation are also manageable. Thus the engagement process is an important, and in the case of UCG, a promising task, involving educating the community about the potential economic and environmental promises of UCG, redressing the environmental concerns, fostering respect for the social values and promoting inclusion of stakeholders in the development of formerly uneconomic resources through this technology. Participation is an important indicator of the social aspect of sustainability and helps in quantification of equity by calculating distribution of wealth/benefits within the society [Becker 1997]. Thus, the participation of different stakeholders especially in the formulation of policies directly influencing the community is necessary. This can help improving the status of UCG in public perception.

6.3.2 Question 2 - People

Will people's wellbeing be maintained or improved during and after the project or operation?

6.3.2.1 Objectives

Community organization and capacity, social and cultural integrity, worker and population health and safety

6.3.2.2 UCG Conformity

An important part of corporate social responsibility (CSR) is improvement in the standards of social development and respect for fundamental rights [Shield, Solar et al. 2006]. Keeping in view the economic and environmental aspects of UCG, the development plan should incorporate human wellbeing as an integral part. This may be accomplished by hiring local labor, creating training and development opportunities in the project area, assisting infrastructure development and developing social capital. The economic opportunity provided by the development of neglected mineral resources through UCG should not be a "resource curse" for the community [Davis and Tilton 2005] but an opportunity to develop the community through careful planning, transparency and inclusion. Traditional economic activities in the area should also be promoted to avoid the "Dutch disease", which suggests that increased natural resource exploitation in the area can result in increased labor cost, appreciated local currency and a neglect of manufacturing and agricultural sector, thus an increased export cost for these sectors [Davis and Tilton 2005]. Economic diversification can help in reducing the boom and bust syndrome. Investment in human and social capital can assist in increasing the level of social license to operate. Incorporating people's wellbeing and meeting these concerns in a UCG development plan may be a positive experience, as this technology has potential to give rise to other economic activities such as power generation plants, various chemical industries and a potential site of carbon sequestration process [Clean Air Task Force 2009].

6.3.3 Question 3 - Environment

Is the integrity of the environment assured over the long term?

6.3.3.1 Objectives

Ecosystem function, resilience and self-organizing capacity, ecological entitlement, full ecosystem costs, benefits and risks, responsibilities and sureties, environmental stress and action to ensure ecosystem integrity

6.3.3.2 UCG Conformity

UCG can be utilized to exploit uneconomic, deep seated, low quality coal reserves [Lamb 1977] in an environmentally friendly manner. In addition, the method has a reduced surface footprint over conventional mining, due to lack of transportation and waste management infrastructure requirements and it is environmentally attractive [Creedy, Garner et al. 2001; Burton, Friedmann et al. 2006; Meany and Maynard 2009]. However, studies have shown that UCG has potential for creating environmental problems, such as groundwater contamination through gas escape and leachate [Sury, White et al. 2004]. Other hazards include surface subsidence, hazardous atmospheric emissions, uncontrolled cavity growth and human impacts (noise, dust, increased traffic etc.). Potential environmental hazards of UCG can be mitigated effectively through careful site selection, appropriate operational controls, proper shut down process and effective environment monitoring [Sury, Kirton et al. 2004]. The syngas produced by UCG contains a mixture of CO_2,CO, H_2, CH_4, water and traces of pollutants such as H_2S, HCN, NH_3 and other gases[Creedy, Garner et al. 2001; Burton, Friedmann et al. 2006]. The composition of raw product gas is similar to that produced by surface gasifiers, and cleaning technology for such gas compositions is already available [Creedy, Garner et al. 2001]. In order to avoid flow of contaminations from the cavity to the underground water table and to minimize loss of organic laden gases, the pressure in the UCG cavity must be maintained below hydrostatic. This will ensure a small and continuous influx of water into the cavity to aid the burning process and minimize environmental impacts [Shafirovich and Varma 2009].

UCG consumes the coal underground and produces a burn cavity in the subsurface. This cavity increases in dimensions with the progress of the process and can result in potential surface deformation. [Friedmann 2009]. UCG-induced subsidence is expected to progress depending on the geometry of the cavity and depth—the greater the depth, the smaller the chances of subsidence, depending upon the mechanical properties of rock and stress regime in the area [Creedy, Garner et al. 2001]. However, most experimental work conducted for UCG did not report any significant surface subsidence, possibly because of the small size of active operations. For commercial large-scale projects, however, more focused research is required for assessing, managing and reducing the subsidence impacts of UCG [Friedmann 2009] .

CO_2 is a main component of UCG product gas and may be present in the range of 25-40%. Integration of UCG with carbon capture and sequestration (CCS) may result in a critical climate change mitigation technology to produce power from coal, and many studies suggest it as a low cost, above ground, low carbon form of coal power production [Redman, Fenerty et al. 2009]. This indicates that UCG is a technology that has environmental promise and presents an excellent solution particularly for extracting energy from "unminable" coal seams. Through careful planning and proper site selection, the hazards of UCG can be minimized significantly. It is worth noting that only two of over 30 UCG trials in the U.S. resulted in clear evidence of environmental contamination [Burton, Friedmann et al.].

6.3.4 Question 4 - Economy

Is the economic viability of the project or operation assured, and will the economy of the community and beyond be better off as a result?

6.3.4.1 Objectives

Project or operation economics, operational efficiencies, economic contributions: annual/total, community/regional economies

6.3.4.2 UCG Conformity

UCG not only provides an excellent economic opportunity by developing otherwise uneconomic, abandoned and discarded natural resources but also by promoting a polygeneration mix of industries such as power generation, chemicals, Fisher-Tropsch and methanol. UCG helps in maximizing indigenous energy reserves, reduced vulnerability to imported oil and security of supply [Courtney September 2009]. UCG increases the amount of coal available by exploiting unminable coals. As indicated by Courtney [Courtney September 2009], estimated total world coal resources are 5-8,000 billion tons (Bt) with proven coal reserves of 909 Bt as of 2009. The estimated addition by UCG is 600 Bt. Similarly, Burton et al. [Burton, Friedmann et al. 2006] suggest a possibility of a 300-400% increase in the recoverable U.S. coal reserves through the application of UCG. This provides an economic opportunity in the project areas, and may help in the development of infrastructure, enhanced health and educational facilities and improved community relations through sharing of benefits, costs and risks. As indicated by Yang et al. [Yang, Zhang et al. 2008] UCG can prove an excellent source for large scale H_2 production. UCG can utilize the current infrastructure for gas transportation, if available in the vicinity, thus reducing capital and operating costs of the project. Ze-gen, Inc. is planning to develop this technology in small modules that can be used to provide product gas to existing industrial consumers of natural gas and fuel oil or alternatively, to blend the natural gas with product gas through the existing pipeline infrastructure [Redman, Fenerty et al. 2009]. This provides another economic boost for this technology.

6.3.5 Question 5 - Traditional and Non-market Activities

Are traditional and non-market activities in the community and surrounding area accounted for in a way that is acceptable to the local people?

6.3.5.1 Objectives

Maintenance of activity/use levels, maintenance of traditional cultural attributes

6.3.5.2 UCG Conformity

Since UCG provides an economic resource for the community, it is emphasized that operations must be planned to avoid conflicts with traditional and non-market activities in the project area. This is feasible in the case of UCG, since it has minimal surface disruption. The operations may be planned to avoid hunting areas or fishing ponds, if any, in the project area. Vocational training institutes can be developed in the area to promote housework and traditional crafts. Respect and preservation of local religious sites and customs is important, in not only improving traditional and non-market activities, but also in the trust building for the project.

6.3.6 Question 6 - Institutional Arrangements & Governance

Are rules, incentives, programs and capacities in place to address project or operational consequences?

6.3.6.1 Objectives

Mix of rules, market incentives, voluntary programs and cultural norms, capacity, bridging, confidence that commitments made will be fulfilled

6.3.6.2 UCG Conformity

Since UCG is currently emerging as a “clean” and economic alternative of energy generation from coal, several governments are interested in capitalizing on this opportunity. For example, a commercial trial is undergoing in Australia with government support. Similarly, governments in China and India are encouraging UCG amid internal and external pressures of pollution control and environment management [Creedy, Garner et al. 2001]. The incentives in the form of cap and trade legislations and carbon credits have promoted interest in this technology. Several research and development institutes are established in various countries to promote research on UCG and its integration to CCS [Creedy, Garner et al. 2001]. In addition, regulations regimes are either in place or currently being drafted in various countries regarding UCG [Creedy, Garner et al. 2001; Sury, Kirton et al. 2004; Sury, White et al. 2004].

6.3.7 Question 7 - Synthesis and Continuous Learning

Does a full synthesis show that the net result will be positive or negative in the long term, and will there be periodic reassessments?

6.3.7.1 Objectives

Continuous learning and improvement, overall synthesis, strategic level alternatives.

6.3.7.2 UCG Conformity

The overall status of UCG development is very encouraging and positive. A renewed interest is emerging worldwide in this technology, leading to more research and development. For example, China is developing technology to apply UCG on abandoned mineshafts and has executed at least sixteen pilot projects since 1991 [Ray, Panigrahi et al. 2010]. Similarly, India, Australia, Europe, UK, New Zealand, Japan and several other countries are promoting UCG research. In the U.S., though federal and state governments are not currently funding research, several private companies and organizations are encouraging R&D in this field. This ensures that a continuous learning process is in place for this technology, resulting in improvement of operational processes, environment monitoring, capacity building and human capital.

6.4 The Natural Step (TNS) Framework

The Natural Step (TNS) framework is a tool that provides a systematic way of understanding and planning towards sustainable development. The main concept of this framework is simplicity without reduction, which means that understanding the defining principle of a given system makes it easier to comprehend the complexity of details within the system.[Broman 2000]. TNS is a comprehensive model of strategic planning and decision making towards sustainable development. The framework has the following main components [Townsend and MacLellan 2010]:

- The funnel
- The sustainable principles for a sustainable society
- Backcasting
- A four stage ABCD strategic planning process.

6.4.1 The Funnel

The funnel is a metaphor that represents the degrading nature of available resources and ecosystem, with the narrowing walls of a funnel indicating the decreasing options to operate [Broman 2000]. These walls grow closer because of non-sustainable activities, growing demand of resources and declining ability of earth to provide these resources. However, an indicator of sustainable development is a system or process that has the capability to widen the narrowing walls of this funnel. UCG is a process that has the ability to increase available coal reserves through exploitation of low-grade, uneconomic, deep-seated coal seams. It also has the ability to harness energy from the abandoned or previously used coal mines, some of which may contain as much as 50% of the original coal [Lamb 1977]. The challenge for sustainability is to avoid hitting the wall while reducing the pressure so that the funnel may open again [The Natural Step USA]. UCG satisfies this challenge by increasing resources and decreasing economic and environmental pressures.

6.4.2 The sustainable principles for a sustainable society

Basic principles for sustainability are defined in TNS [Broman 2000] as:

- For society to be sustainable, the ecosphere must not be systematically subject to
    - increasing concentrations of substances from the earth's crust
    - increasing concentrations of substances produced by the society
    - impoverishing physical manipulation or over-harvesting
- For society to be sustainable, resources must be used efficiently and fairly to meet basic human needs worldwide.

UCG conforms to these principles as it utilizes the substances from the earth's crust that have been discarded and declared uneconomic, used inefficiently or still in place due to technical limitations. It increases the earth's resource potential. Although this process uses the substances from earth's crust, it provides an alternative and efficient way of using the abandoned resources. UCG is very efficient in energy utilization as it eliminates the energy wasted in transportation of the mineral waste and usable material to the surface from underground [Burton, Friedmann et al. 2006]. Similarly, it harvests energy from the previously wasted material and re-circulates that energy into the system.

6.4.3 Backcasting

Backcasting is a methodology in which a successful and sustainable outcome of an activity is envisioned and strategies are developed to link that outcome to the present situation. The processes are then developed based on sustainability principles to attain the desired outcome. The sustainable future of UCG technology is a product gas without any hazardous discharges and a clean energy source utilizing natural resources efficiently. Thus backcasting promotes the integration of UCG with carbon capture and storage (CCS) technology. The ideal scenario is to capture CO_2 from the product gas at the source and sequester it near the project area to avoid transportation costs. The technology exists to capture CO_2 from the syngas and to store it in the geological formations; however, research is in progress on the reactor zone carbon sequestration, aiming to store CO_2 in the voids and cavities created by UCG processes [Friedmann 2009].

6.4.4 The ABCD Planning Process

The ABCD process is an integral part of the TNS framework that helps strategic planning for the sustainable future. ABCD consists of four basic steps; Awareness, Baseline Analysis, Compelling Vision and Down to Action [The Natural Step USA]. Awareness of sustainable development principles enables organizations to develop strategies to achieve the desired outcomes through inclusion of sustainable development principles in corporate planning. Baseline analysis helps in the assessment of current situations and points out the activities and practices that are violation of these principles. Compelling visions are solutions and innovations that are obtained by applying the constraints of sustainable development principles. Down to Action represents the actual implementation of developed strategies and solutions. These planning steps advocate further research and development on integration of UCG and CCS to achieve the envisioned future of UCG as a clean energy generating technology.

6.5 Green Engineering

Green Engineering is a framework for creative engineering solutions and innovative approaches to solve the problems involving environment, economy and society throughout the lifetime of the project. The framework consists of 12 principles that provide a basis for making engineering solutions more sustainable. These principles are set as guidelines to use in sustainable development and to address sustainability challenges through effective design [Mihelcic and Zimmerman 2010] . Table 6.1 presents the principles of green engineering and their application to UCG in general. Specific design details, which correspond to these principles, largely depend upon the specific site conditions and project environment; however, Table 6.1 below presents the general conformity of UCG to these principles.

Table 6.1: UCG and Green Engineering Principles

12 Principles of Green Engineering [Anastas and Zimmerman 2003]	**UCG Compatibility**
Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently non-hazardous as possible.	The input for UCG is low quality and deep-seated coals and/or abandoned coal insitu. This coal generally is not recovered by conventional mining and is a wasted resource. UCG utilizes this wasted material and converts it into usable energy. The output is in the form of syngas that has the potential, through the integration of UCG and CCS, to be converted into an economical clean energy source. This principle is compatible with the technology and ensures that strategies of environment management are included in the development plan for UCG projects.
It is better to prevent waste than to treat or clean up waste after it is formed.	UCG process reduces the waste production as no coal is transported to the surface. It reduces the resulting dust as well. Majority of hazardous materials including ash and many pollutants (mercury, particulates and sulfur species) are greatly reduced in volume [Burton, Friedmann et al. 2006]. As there is no or minimal water discharge to the surface, wastewater management is very easy. This makes UCG conformable to this principle.

Separation and purification operations should be designed to minimize energy consumption and materials use.	Research is continuing to integrate carbon capture and sequestration to UCG at the site, thus reducing CO_2 and transportation costs and energy consumption. The surface footprint of UCG is less, compared to other coal exploiting technologies. The purification of product gas can make it a “clean energy” source.
Products, processes, and systems should be designed to maximize mass, energy, space and time efficiency.	UCG increases the efficiency of energy production and can enhance the energy recovery from coal seam over 75% [Burton, Friedmann et al. 2006]. It also recovers entrapped methane from the coal seam regardless of its economic value thus maximizing energy efficiency.
Products, processes and systems should be "output pulled" rather than "input pushed" with energy and materials.	The input for this process is air or oxygen at elevated pressure and low quality coal, whereas output is a flow of product gas at high temperature and pressure. This product gas generates energy for several uses. Utilizing lower cost inputs, a valuable output is obtained.
Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse or beneficial disposition.	Though UCG is non-renewable and does not support recycling, it reuses abandoned resources. It can increase the energy efficiency from exploitation of natural resources.
Targeted durability, not immortality, should be a design goal.	The process is durable depending upon the extent of coal availability. It also promotes other industrial venues in the project area thus increasing economic life of the project.
Design for unnecessary capacity or capability (e.g., "one size fits	The design for UCG depends upon specific site characteristics and geo-mechanical conditions of

all") solutions should be considered a design flaw.	the area. It is difficult, therefore, to generalize and implement the design from one site to other. Thus, it promotes design for each site that is based on general principles, but accommodating the peculiarity of site.
Material diversity in multi-component products should be minimized to promote disassembly and value retention.	Since there is minimal disruption of surface for this technology, the land use for various purposes is encouraged during and after the closure of project. As an example, it does not interfere with hunting habitats in the project area.
Design of products, processes and systems must include integration and interconnectivity with available energy and materials flows.	UCG provides more economic potential if the use of product gas be in close proximity of the project area. A power generation or chemical plant directly fed by product gas can increase economic efficiency and reduce the transportation costs.
Products, processes and systems should be designed for performance in a commercial "afterlife."	The product gas can be used as a feedstock for several chemical industries. It can be used as a fuel for power generation. Thus, the energy provided by this technology can enhance value addition for several products.
Material and energy inputs should be renewable rather than depleting.	The UCG and other mineral related processes are not regarded renewable. However, with the development of new technologies that offset the cost-increasing effects of depletion, mining can be sustainable. This means that with the increasing cost of mineral commodities due to decrease in their availability or exploitation of low-grade reserves, there is also an increasing

	trend towards development of technologies that are low cost and can offset this upward pressure. Thus, cost-increasing effects of depletion and cost-decreasing effects of new technologies determine the long run availability of mineral commodities [Tilton 2009]. This opportunity cost paradigm is also applicable to UCG and according to [Tilton 2009], is a more appropriate way to assess the future threat of depletion to sustainability.

6.6 Other Sustainable Development Frameworks

Several other frameworks are available that can effectively help in assessing the contribution of a project towards sustainable development. The examples include 10 principles of ICMM (International Council on Mining and Metals), Design for X, Life Cycle Assessment (LCA) and several others. The 10 principles of ICMM are essentially based on issues defined in MMSD and provide a framework for comparing the current standards with relevant conventions and guidelines, for example, the Rio Declaration, the Global Reporting Initiative, the Global Compact, OECD Guidelines on Multinational Enterprises, World Bank Operational Guidelines, OECD Convention on Combating Bribery, ILO Conventions and the Voluntary Principles on Security and Human Rights [ICMM. 2010]. Similarly, a number of indicators and matrices are available that evaluate and assess the contribution of any project towards sustainability. For example, the United Nations has a comprehensive set of indicators that measure sustainable development and provide a framework and methodology to attain sustainability [Division for Sustainable Development 2001]. UCG as a promising new technology conforms to several of these other frameworks and, depending upon specific site conditions, indicates the potential for positive social, economic and environmental correlation towards sustainable development and a sustainable future.

6.7 Chapter Conclusions

As stated by Gibson et al. [Gibson et al. 2010], assessments are exercises in evaluation and decision making. They provide a number of options about further reviews, design changes, impact evaluations and process improvement. The idea of sustainability assessments in the case of UCG is to examine whether this technology has positive correlation with sustainable development principles and explore further research and development opportunities. A number of frameworks and indicators, developed over the last two decades to define sustainability and sustainable development have gained acceptance as valuable tools for understanding sustainability as a concept and incorporating sustainable development principles as an integral part of corporate planning. UCG conforms readily to these frameworks as indicated in this chapter. However, almost all frameworks indicate the need to devote a major research effort towards integration of UCG and CCS. This integration can help development of UCG as a clean, sustainable and economic alternative of energy production through exploitation of unminable and abandoned coal reserves.

Chapter 7 - Greenhouse Gas Reduction Potential of UCG

7.1 Introduction[2]

Underground coal gasification (UCG) is an advancing technology that is receiving considerable global attention as an economic and environmentally friendly alternative for exploitation of coal deposits. This technology has the potential to decrease greenhouse gas emissions during the development of coal deposits. The environmental benefits of UCG that promote reduction in greenhouse gas emissions include elimination of conventional mining, coal washing and fines disposal, coal stockpiling and coal transportation activities. Additional benefits include; a smaller surface area requirement with minimal surface disruption; removal of CO_2 from the syngas at significantly reduced cost as compared to carbon capture and transport from a power plant; and the potential to reduce CH_4 emissions, a potent greenhouse gas. UCG utilizes coalbed methane irrespective of its economic value during the burning process and increases energy efficiency. The CH_4 in the product gas is consumed completely during power and/or electricity generation, thus reducing overall methane emissions to the atmosphere.

This chapter compares greenhouse gas emissions from conventional mining methods to UCG for the exploitation of a coal reserve. The findings indicate that UCG reduces greenhouse gas emissions significantly as compared to other competitive coal exploiting technologies. This research may help in the selection of a suitable method to develop coal deposits when the reduction of greenhouse gases is an essential part of planning.

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[2] This chapter is based on the following paper: Hyder, Z., Ripepi, N., Karmis, M., *Underground Coal Gasification and Potential for Greenhouse Gas Emissions Reduction*, CMTC 151155-MS, 2012 Carbon Management Technology Conference, February 7–9 2012, Orlando, Florida, USA DOI: 10.7122/151155-MS, ISBN: 978-1-61399-179-4.
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7.2 Factors aiding to GHG Reduction Potential

UCG has the potential to reduce greenhouse gas (GHG) emissions when exploiting a coal reserve. The simplicity of the process, elimination of conventional mining, the complete removal of coal transportation and stockpiling needs, reduced surface footprint, minimal waste and water management requirements, consumption of coalbed methane and synergy with carbon capture and sequestration are some of the factors that help in the reduced GHG emissions. The following is a detailed account of these factors and their GHG reduction potential.

7.3 Elimination of Conventional Mining

According to the International Energy Agency, the global demand for energy will increase by one third between 2010 and 2035, with a 20% increase in energy-related CO_2 emissions. To meet this energy requirement, coal demand will continue to increase for the next ten years and will then stabilize, ending around 17% higher than in 2010 [IEA. 2011]. This highlights the importance of coal in the next generation's energy mix and emphasizes the need of concentrated efforts for promotion and development of new technologies that help harvesting energy from coal deposits with reduced environmental impacts and GHG emissions. A unique aspect of UCG that makes it an economically and environmentally attractive technology is the elimination of conventional mining requirements for exploitation of coal deposits, especially in low grade, thin coal seams. A life cycle assessment of any coal mine reveals that a significant part of the total GHG emissions is contributed by diesel, gasoline and electricity used by the equipment required for mine development, processing, operation and coal transportation [Ditsele and Awuah-Offei 2010]. UCG eliminates the need for development of mining infrastructure such as shafts, inclines, tunnels, galleries and panels, thus eliminating a large portion of GHG emissions resulting from these activities. Ditsele and Offei indicate that the use of machinery and equipment for mining activities contributes approximately 50% of total GHG emissions from a mine [Ditsele and Awuah-Offei 2010]. This means that elimination of conventional mining activities can result in considerable reduction of GHG emissions load.

7.4 No Coal Transportation on Surface

With UCG, the entire coal gasification takes place underground; thus, there is no coal transportation to the surface. This eliminates GHG emissions related to coal transportation from underground workings to the surface for storage and distribution. It also eliminates the need for surface gasifiers for conversion of coal to gas, which provides a significant economic and environmental advantage. The product gas can be transported to gas cleaning facilities and other industrial establishments for use via the surface pipeline network, thus reducing the GHG emissions linked to coal transportation to industrial units and/or electric power generation plants via diesel or gasoline transport. As indicated by Jaramillo et al., gasoline and diesel transport adds between 17 to 20 g of CO_2 per liter of gasoline and between 21 and 25g of CO_2 per liter of diesel [Jaramillo, Samaras et al. 2009]. Thus, a significant amount of GHG emissions can be reduced just by eliminating coal transport to and from the surface.

7.5 No Storage Requirement

In the UCG process, there is no coal movement out of the strata. The coal is burned underground and the product comes out in the form of heated gases, thus eliminating the need for coal storage and stockpiling. Since there is no waste movement up ground as well, this also eliminates the GHG emissions from the waste material that is usually dumped into the spoil piles behind the active mining area and from the tailings and reject dumps of coal preparation plants. These spoils and rejects contain significant amount of carbonaceous material and generate greenhouse gases, especially CH_4 and CO_2, along with some other gases, through spontaneous combustion and low-temperature oxidation [Carras, Day et al. 2009]. A study by Carras et al. (2009) on greenhouse gas emissions from low-temperature oxidation and spontaneous combustion at open-cut coal mines in Australia found that the average emission rate of GHG for active spontaneous combustion with marked surface signs was 8200 $kgyr^{-1}m^{-2}$. The average emission rates of CO_2 and CH_4 for rejects were 95 $mgs^{-1}m^{-2}$ and 4.7 $mgs^{-1}m^{-2}$, respectively, from sites with high emission rates. Thus by using the coal insitu, UCG reduces a significant amount of GHG by eliminating need for coal stocking and processing.

7.6 Reduced Surface Utilization

UCG requires a smaller surface area for exploitation of the coal reserve compared to other coal exploiting technologies. This technology also has a smaller surface footprint at power stations [Creedy, Garner et al. 2001]. As compared to conventional mining or surface gasification plants, the surface impact of UCG is highly localized, as the primary process is underground. This reduced surface impact and minimal surface requirement can improve the reduction of GHG by preservation or regeneration of vegetation at the UCG site.

Another important aspect with respect to surface utilization is its availability for a mix of different energy resources. A study by Chavez-Rodriguez and Nebra (2010), assessing the GHG emissions from different fuel sources reveals the importance of including coal, renewables, oil and nuclear in the energy mix. The study estimated that by 2030, in order to fulfill the annual fuel requirement for the transportation sector of 1,924 GL of gasoline and 444 GL of ethanol, 30.2 Mha of tropical forest or 2,373 Mha of dry land forest would be required for gasoline GHG neutralization. If total ethanol demand was supplied by sugar cane ethanol, an area of 57.7 Mha of production land would be required as well as 1.3 Mha of tropical forests or 174 Mha of dry land forests as carbon uptake land [Chavez-Rodriguez and Nebra 2010]. This indicates the importance of surface utilization from different energy resources and highlights the savings that UCG can bring forward.

Ongoing advancements in drilling technology are further reducing the surface requirements and disruption by UCG. For example, advances in directional drilling allow horizontal inseam wells for better linkage between injection and production wells, reducing the number of wells required to consume a specific deposit. A directionally drilled 600 m (1,968 ft.) long panel accessed by one well pair in a 7 m (23 ft.) thick seam can gasify between 125,000 to 175,000 tonnes of coal (~137,000 to 192,000 tons), depending on which panel design is used [Ahner 2008]. This means that to utilize a one million ton of coal deposit, only 4 to 5 pair of wells will be required.

7.7 Usage of CH_4

CH_4 (methane) has a much lower concentration in the atmosphere as compared to CO_2, but it is 23 times more potent as a GHG than CO_2 [Wightman 2006; Archer 2011]. CH_4 is usually entrapped in the coalbed during coal formation. During coal mining activities, this gas releases due to strata relaxation and changes in pressure gradient. An important consideration is the total amount of methane entrapped in the coalbed. The amount of methane released depends upon coal rank, seam depth and mining method, with underground coal mining releasing more methane than surface or open pit mining because higher gas contents are typically found in deeper seams [Irving and Tailakov 2000]. The gas retained in coalbeds ranges from negligible quantity to about 900 cubic feet per ton (25.48 cubic m per ton) [Delucchi 2003]. As estimated by the EPA, in 1997 the methane emissions from coal mines were about 18.8 MMTCE, which accounted for 10% of the U.S. anthropogenic methane emissions for that year [EPA. 1999b]. If the methane is not present in commercial quantity, it is generally vented to the atmosphere through a ventilation network or through degasification systems before or after mining. However, if it is present in commercial quantities, it can be recovered through inseam drilling for commercial purposes. If commercially recoverable quantities of coalbed methane are present, though, then another dispute may arise in the sequence of energy recovery from coal seams [Couch 2009].

UCG utilizes coalbed methane irrespective of its commercial value. The presence of CH_4 may enhance the heating value of product gas and may aid the burning process. Thus, whatever quantity of methane is present in the seam, UCG will consume it during the burning process, which in turn, will reduce the GHG emissions load for coal utilization.

7.8 Carbon Capture and Sequestration Potential

An important aspect of UCG is its synergy with carbon capture and sequestration. As stated by Burton et al. (2006), it is much easier to remove CO_2 from the syngas than from the flue gas. A number of technologies to remove CO_2 from syngas are readily available [Burton, Friedmann et al. 2006]. UCG provides low cost electricity generation from coal even with CO_2 capture, when compared with both IGCC and post-combustion capture from a pulverized coal power plant [Clean Air Task Force 2009]. Integration of UCG with carbon capture and sequestration (CCS) may result in a critical climate change mitigation technology. Many studies suggest it is a low cost, above ground, low carbon form of coal power production [Redman, Fenerty et al. 2009].

UCG also provides an alternate for geological storage of CO_2. The well infrastructure of UCG provides a source for geological storage of CO_2 and results in reduced capital and operating expenses for the combined process [Friedmann 2009]. As stated by Ray et al., coal gasification with CCS, surface or underground, offers a practical medium-term option for the continuing use of coal as a bridging strategy to eventual energy production with zero emissions, i.e., renewable energy and the hydrogen economy [Ray, Panigrahi et al. 2010]. There is a developing interest in utilizing the UCG burn cavity for carbon sequestration, and research is underway to further study in this potential of UCG and its environmental impacts.

7.9 Less Pollutant Movement to Surface

The syngas produced by UCG contains a mixture of CO_2,CO, H_2, CH_4, water and traces of pollutants such as H_2S, HCN, NH_3 and other gases [Creedy, Garner et al. 2001; Burton, Friedmann et al. 2006]. The composition of raw product gas is similar to that produced by surface gasifiers, and cleaning technology for such gas compositions is already available [Creedy, Garner et al. 2001]. Generally, sulfur and nitrogen report to the surface with the gas, whereas ash and most heavy metals remain in the cavity [Fergusson 2009]. The process eliminates production of some criteria pollutants (e.g., SO_x, NO_x) and reduces the volume of mercury, particulates and sulfur species production, which makes the handling of pollutants easier [Burton, Friedmann et al. 2006]. The decreased pollutant production and movement reduces the cost of waste treatment and handling. The reduced volume of waste at the surface also decreases GHG emissions from the waste spoils and reduces some other environmental effects like acid mine drainage, generally caused by action of surface water on waste piles.

7.10 Chapter Conclusions

In the today's era of growing energy demand and increased concern about environmental issues, the importance of technologies that can provide economic and environmentally friendly energy resources is inevitable. These energy demands and environmental concerns require an energy mix from all available resources, including coal, petroleum, natural gas, renewables, nuclear and solar. No single resource, either renewable or nonrenewable, can fulfill both the energy demand and environmental sustainability without some compromise. As an example, UCG with electricity generation may likely result in GHG emissions 25% lower than conventional coal electricity generation, but 75% higher than natural gas electricity generation [Moorhouse, Huot et al. 2010] . However, a recent study from Cornell finds that natural gas from fracking could be 'dirtier' than coal, as fracking , venting and leaks would release 3.6% to 7.9% of methane over the life time of the well, which represent a methane emissions at least 30% more and perhaps more than twice as great as those from conventional gas [Howarth, Santoro et al. 2011; Shackford 2011]. This means all the resources are needed to be developed with the emphasis on development of technologies that can harness energy from these resources in an economic and environmentally friendly manner without discarding/discrediting any option. UCG in integration with CCS provides such an option to develop coal deposits for cheaper, cleaner energy sources because capturing the CO_2 stream is easier, doesn't require the same capital investments as other technologies, and provides a potential of GHG reduction.

Chapter 8 - Comparing Life Cycle Greenhouse Emissions from Coal and UCG Power Generation

8.1 Introduction

Coal is the most abundant fossil fuel worldwide, with about one trillion tonnes in reserves, sufficient for about 150 years at the current production rates. Coal demand as an energy resource is increasing and will continue to increase for the next ten years and then stabilize at a level around 17% higher than the 2010 level [IEA. 2011]. There is a projected increase of 20% in global coal production between 2009 and 2035 with 90% of the projected energy demand coming for non-OECD economies. Coal is the second largest primary fuel used in the world and the backbone of electricity generation [IEA. 2011] .

In the U.S., coal is also a major energy source and more than 25% of world's recoverable coal reserves are in the U.S. The U.S. uses around 1.1 billion tons of coal per year. In 2010, the U.S. produced 932 million tonnes of hard coal and 63 million tonnes of brown coal [IEA. 2011]. As of January 1, 2011, the DRB (demonstrated reserve base) for the U.S. was estimated to contain 485 billion short tons [EIA. 2012b]. Of the estimated recoverable coal reserves in the world, the U.S. holds the largest share (27%), followed by Russia (17%), China (13%), and Australia (9%) [DoS. 2010].

However, the U.S. electric power sector's historical reliance on coal-fired power plants has begun to decline. Though coal still remains the dominant energy source for electricity generation, its share of total generation is expected to decline from 45% in 2010 to 39% in 2035. The main reasons for this decline are slow growth in electricity demand, continued competition from natural gas and renewable plants, and the need to comply with new environmental regulations [EIA. 2012a]. As estimated by the U.S. EIA, total coal consumption—including the portion of CTL (coal to liquid) consumed as liquids— will increase from 20.8 quadrillion Btu (1,051 million short tons) in 2010 to 22.1 quadrillion Btu (1,155 million short tons) in 2035, with 2012 as a reference. However, coal consumption, mostly for electric power generation, will fall off through 2015 because of the replacement of the coal-fired power generation with alternate sources. After 2015, coal-fired generation increases slowly as the remaining plants are used more intensively [EIA. 2012a].

Electricity generation currently accounts for 93% of total U.S. coal consumption [EIA. 2012a]. Coal, the fuel most frequently used for power generation and supplying over 48% of the total electricity generated in the United States, also has the highest emissions of carbon dioxide (CO_2) per unit of energy [DoS. 2010]. Electricity generators consumed 36% of U.S. energy from fossil fuels and emitted 42% of the CO_2 from fossil fuel combustion in 2007 and in 2010 electricity generation from coal was the largest emitter of GHGs with coal combustion for electricity accounting for 1827.3 Tg CO_2 equivalent [EPA. 2012]. Coal mining, transportation, washing and disposal pose a risk to human health and coal combustion emissions may damage the respiratory, cardiovascular and nervous systems [Lockwood, Welker-Hood et al. 2009].

The importance of coal in the future energy mix, its potential environmental impacts, difficult mining conditions, stringent environmental regulations, strong competition from other energy sources and depletion of most accessible and low cost reserves have made it imperative to explore for economic and environmentally friendly alternatives to traditional coal mining and utilization technologies [Hyder, Ripepi et al. 2011]. One such promising technology is UCG.

UCG is an alternative to conventional coal mining and involves insitu burning and conversion of coal into a gaseous product. The gaseous product or syngas is largely composed of CH_4, H_2, CO and CO_2 with some trace gases and its calorific value ranges between 850 to 1200 kcal/Nm^3 [Ghose and Paul 2007]. The composition and calorific value of syngas depends upon the specific site conditions and type of oxidant (air, stream or oxygen), with typical calorific value (4.0-5.5 MJ/m^3) of air-injected syngas doubling with injection of oxygen instead of air [Walker 1999].

UCG has great economic and environmental benefits when compared to conventional coal mining, surface gasification processes and even coalbed methane drainage procedures [Meany and Maynard 2009]. In the gasification process ash and heavy minerals remain underground and do not report to surface [Fergusson 2009], thus resulting in decreased waste management cost and related infrastructure. The gasification process requires certain amount of water to facilitate the chemical reaction [Ag Mohamed, Batto et al. 2011], which results in minimal mine water recovery. Requirement of smaller surface area and reduced surface hazard liabilities after abandonment add to the environmental edge of this method over other coal exploiting technologies [Creedy, Garner et al. 2001]. The elimination of conventional mining greatly reduces the environmental problems associated with dirt handling and disposal, coal washing and fines disposal, coal stocking and transportation, thereby resulting in a smaller surface footprint [Creedy, Garner et al. 2001]. During the burning process, UCG not only consumes the coal in the strata but also the entrapped coalbed methane present in the strata. This gives an added advantage to UCG over other coal exploitation methods, where entrapped methane has to be drained either through ventilation system or through venting in the atmosphere [EPA. 2010]. As reported by EPA, the methane emissions from natural gas systems were 6.6 Tg in 2010 and for coal mines the figure was 4.9 Tg [EPA. 1999a].

Like all other technologies, UCG possesses some environmental risks, if the operations are not managed adequately. Major environmental concerns of this technology are ground water contamination and surface subsidence. In the gasification process a number of organic and inorganic compounds including phenols, polycyclic aromatic hydrocarbons, benzene, ammonia, sulfides, carbon dioxide and carbon monoxide are generated that can migrate out of the reaction zone and contaminate the surrounding water [Burton, Friedmann et al. 2006]. The cavities created by UCG resemble long wall panels and result in the unsupported rocks and strata overlying the cavity. This unsupported mass will gradually settle or subside and the effect can reach the surface depending upon the size of cavity, type of strata, depth of coalbed and strength of surrounding rocks. The impacts of subsidence include damage to surface structures and facilities like roads, pipes and buildings, loss of agricultural land through formation of surface fissures, changes in ground slope and surface drainage and hydrological changes including changes in water quantity, quality and flow paths [Blodgett and Kuipers 2002].

The syngas produced by UCG contains a component of vaporized or produced water that may contain residual hydrocarbons, benzenes, phenols and polycyclic hydrocarbons

[Moorhouse, Huot et al. 2010]. These water vapors need to be removed before combusting the gas in a power plant. If mixed with surface water streams and channels, this water has the potential to contaminate them. These water vapors are however, fully treatable and industries have been treating these products for about 60 years [Moorhouse, Huot et al. 2010].

The atmospheric emissions from the UCG process include emissions during the process and emissions during the transport and use of syngas. Combustion of product gas and transport to other location produces harmful pollutants, however the actual UCG process itself does not contribute criteria pollutants to the atmosphere [Ag Mohamed, Batto et al. 2011]. The main emissions from UCG include CH_4, CO_2, CO, H_2, S, organic N_2, H_2S and NH_3; however, the pollutants can be separated from the product gas using proven technologies like cyclones, bag-house filters and electrostatic precipitators [Creedy, Garner et al. 2001; Ray, Panigrahi et al. 2010].

The potential environmental advantages and possible impacts of UCG theoretically establish this technology environmentally superior to other coal exploiting technologies; however, a detailed quantitative analysis in terms of environmental impacts can ascertain these environmental superiority claims. This can be achieved through Life Cycle Assessment (LCA) of competitive technologies. LCA is a tool used for assessment of potential environmental impacts and resources used throughout the life cycle of a product including raw material acquisition, production, use and final waste management phase including both disposal or recycling [Finnveden, Hauschild et al. 2009]. The term product includes both goods and services. The LCA helps in quantifying the impacts of a product or service on different environmental categories including resource utilization, human health and natural ecological systems and assists in identifying the opportunities to improve environmental impacts of a product during its life cycle, better strategic planning and product marketing through quantification of different impacts [ISO. 2006].

In this chapter, the life cycle of UCG from gasification to utilization for electricity generation is analyzed and compared with the coal extraction through conventional coal mining and utilization of coal in power plants. The comparison of life cycle GHG emissions of coal mining and gasification and power generation through conventional pulverized coal fired power plants, supercritical coal fired (SCPC) power plants and integrated gasification combined cycle plants for coal (Coal-IGCC) and UCG (UCG-IGCC) is made. The results of this analysis and comparison of various impacts are discussed in this chapter.

8.2 Methodology

A series of international standards guide the LCA practices. These standards are published under the umbrella of ISO-14040 series and provide basic guidelines for conducting LCA. In addition to these standards, there are number of practical guidelines and professional codes developed to assist in conducting LCA such as SETAC code of practice, guidelines for environmental LCA from the Netherlands (CML/NOH 1992), the Nordic countries (Nord 1995), Denmark (EDIP 1997) and the U.S. (US-EPA 1993) [Baumann and Tillman 2004]. This chapter follows the guidelines of ISO 14040 series.

LCA has generally four steps including goal and scope definition, inventory analysis, impacts assessment and interpretation termed as improvement assessment by some practitioners [DEAT. 2004]. The life cycle assessment includes all the technical systems, operations, processes, inputs and outputs of natural resources, energy, waste, emissions and transportation required for raw material extraction, production, use and after use of the products [DEAT. 2004]. The phases of LCA are iterative and repetitive as depicted by the model of LCA phases in ISO 14040, shown in Figure 8.1 below [ISO. 2006].

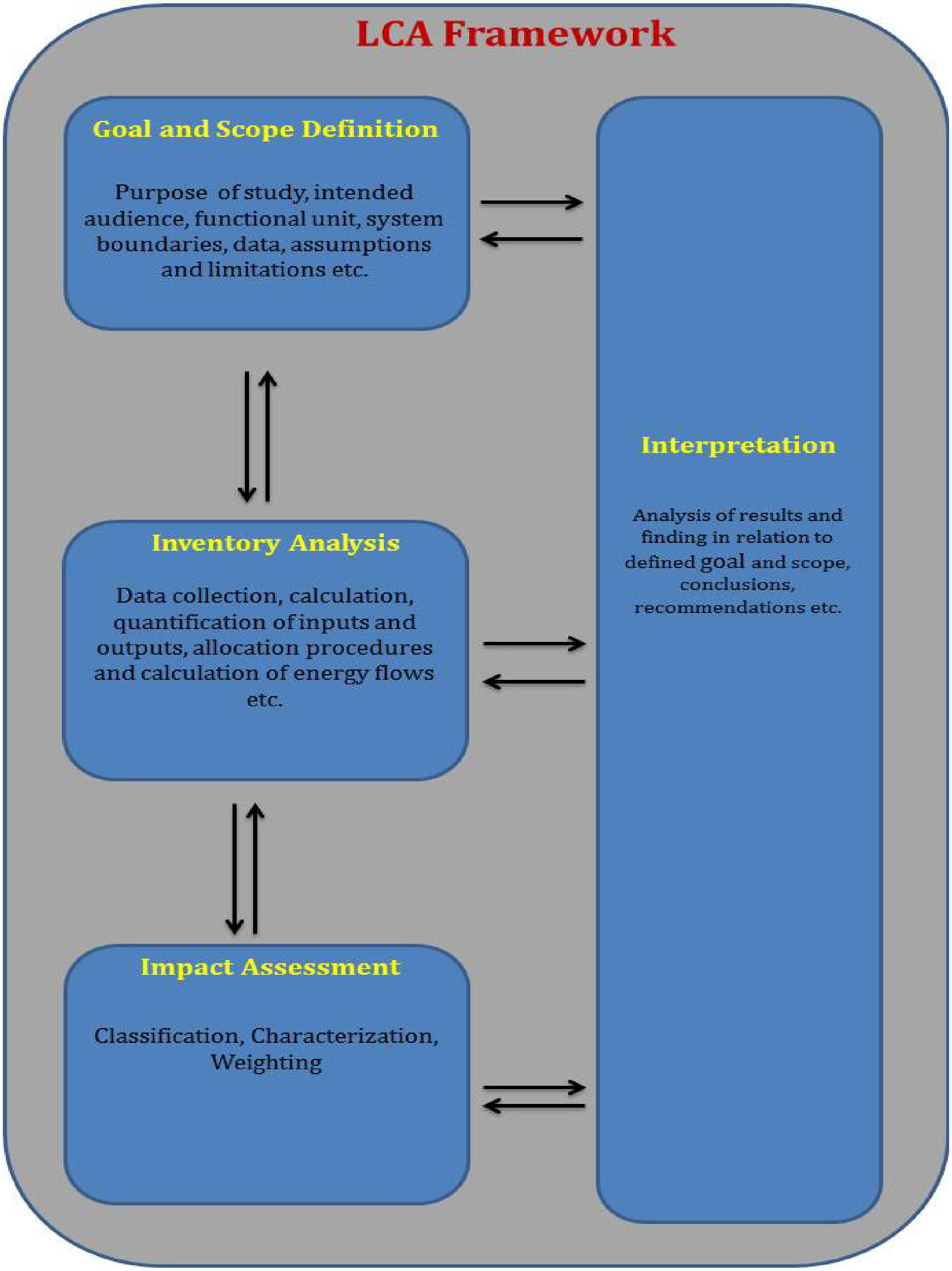


Figure 8.1: Phases of LCA

8.3 Goal and Scope Definition

The goal of this study is to compute life cycle greenhouse gas emissions from electricity generation using coal as primary source, through the following coal based generation alternatives

- Conventional coal fired generation through pulverized coal combustion (PCC) plants, that represent average emissions and generation efficiency of currently operating coal fired power plants
- Generation through supercritical pulverized coal fired (SCPC) power plants, representing advanced technology at increased efficiency
- Generation through integrated gasification combined cycle (IGCC) coal fired power plant i.e. Coal-IGCC, and
- Generation through integrated gasification combined cycle (IGCC) plant using syngas derived from underground coal gasification, i.e. UCG-IGCC

Six main gases categorized as greenhouse gases or GHGs as per Kyoto Protocol, include carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O, hydro fluorocarbons HFCs, Per fluorocarbons PFCs and Sulfur hexafluoride SF6 [United Nations 1998]. Out of these six GHGs, the emissions of only three (CO_2, CH_4, and N_2O) are quantified in this LCA as emissions of other three GHGs (SF_6, PFCs, HFCs) are comparatively negligible in the processes of raw material extraction, electric energy generation, fuel combustion and fugitive losses [PACE 2009].

8.4 Functions and Functional Unit

UCG can be utilized for various purposes including power and electricity generation, hydrogen production, iron reduction, and a chemical feedstock for a variety of chemical products like ethylene, acetic acid, polyolefin, methanol, petrol and synthetic natural gas [Anon 1977; Burton, Friedmann et al. 2006; Yang, Zhang et al. 2008; Courtney 2009; Zorya, JSC Gazprom et al. 2009]. Similarly, coal has various uses including electricity generation, steel production, cement manufacturing and as a liquid fuel [WCA. 2011]. However, to provide a common basis for comparing greenhouse emissions from each system, only the electricity generation is analyzed for each system.

The functional unit measures the performance of functional outputs of the systems by providing a reference to which the inputs and outputs are related and is a quantitative description of the performance of the system(s) in the study [Rebitzer, Ekvall et al. 2004; ISO. 2006]. In this study, the objective is to analyze the amount of greenhouse gas emissions produced by each system; therefore, the functional unit is amount of carbon dioxide equivalent produced per megawatt hour of electricity generation or kgCO_2e/MWh. This functional unit provides a common base for comparing the systems under study.

Carbon dioxide equivalency or CO_2e for different gases is based on the Global Warming Potential (GWP) of these gases. GWP is a relative measure of the amount of heat trapped by a certain mass/volume of a gas compared to the amount of heat trapped by the same mass/volume of carbon dioxide over a discrete time interval [Fulton, Mellquits et al. 2011]. The time interval is generally 20, 100 or 500 years. The Intergovernmental Panel on Climate Change (IPCC) in 2007 estimated the GWP for methane to be 25 times greater than that of CO_2 over a 100-year timeframe and 72 times greater than that of CO_2 over a 20-year timeframe, whereas for nitrous oxide N_2O, these values are 289 for 100-year and 298 for 20-year timeframe [Forster, V. Ramaswamy et al. 2007]. There is a highly polarized debate over the use of 20-year or 100-year timeframe and which source of GWP factors be applied especially in the case of methane [Hughes 2011]. For example, Shindell et al. have estimated the GWP values for methane to be 33 and 105 for 100-year and 20-year timeframes respectively and -560 for NO_x over a 20-year timeframe, based on calculations including interactions between oxides and aerosols, thus giving a substantial net cooling to NOx emissions [Shindell, Faluvegi et al. 2009]. Howarth et al. prefer the use of estimates by Shindell et al. in the calculation of GHG emissions of shale gas production in the U.S. [Howarth, Santoro et al. 2011]. However, the proponents of natural gas generally decline both the use of 20-year time frame and the use of higher GWP values [Hughes 2011].

For this analysis, the GWP values estimated by IPCC in 2007 for 100-year timeframe i.e. 25 for methane and 289 for N_2O are used [Forster, V. Ramaswamy et al. 2007].

8.5 System Boundary

The system boundaries for this study include raw material extraction either in the form of mining or gasification of raw coal, cleaning and processing of coal and gas at a processing plant, transportation of coal and gas to the processing plant and electricity generation facility, utilization in the power generation and disposal of waste resulting from combustion. The emissions from raw material extraction for power plant and mining machinery construction, construction and decommissioning of power plants and other infrastructure, construction of transport systems such as trucks, roads and pipelines for transporting coal and gas are not included in the study. Figure 8.2 and Figure 8.3 show the system boundaries for coal and gasification.

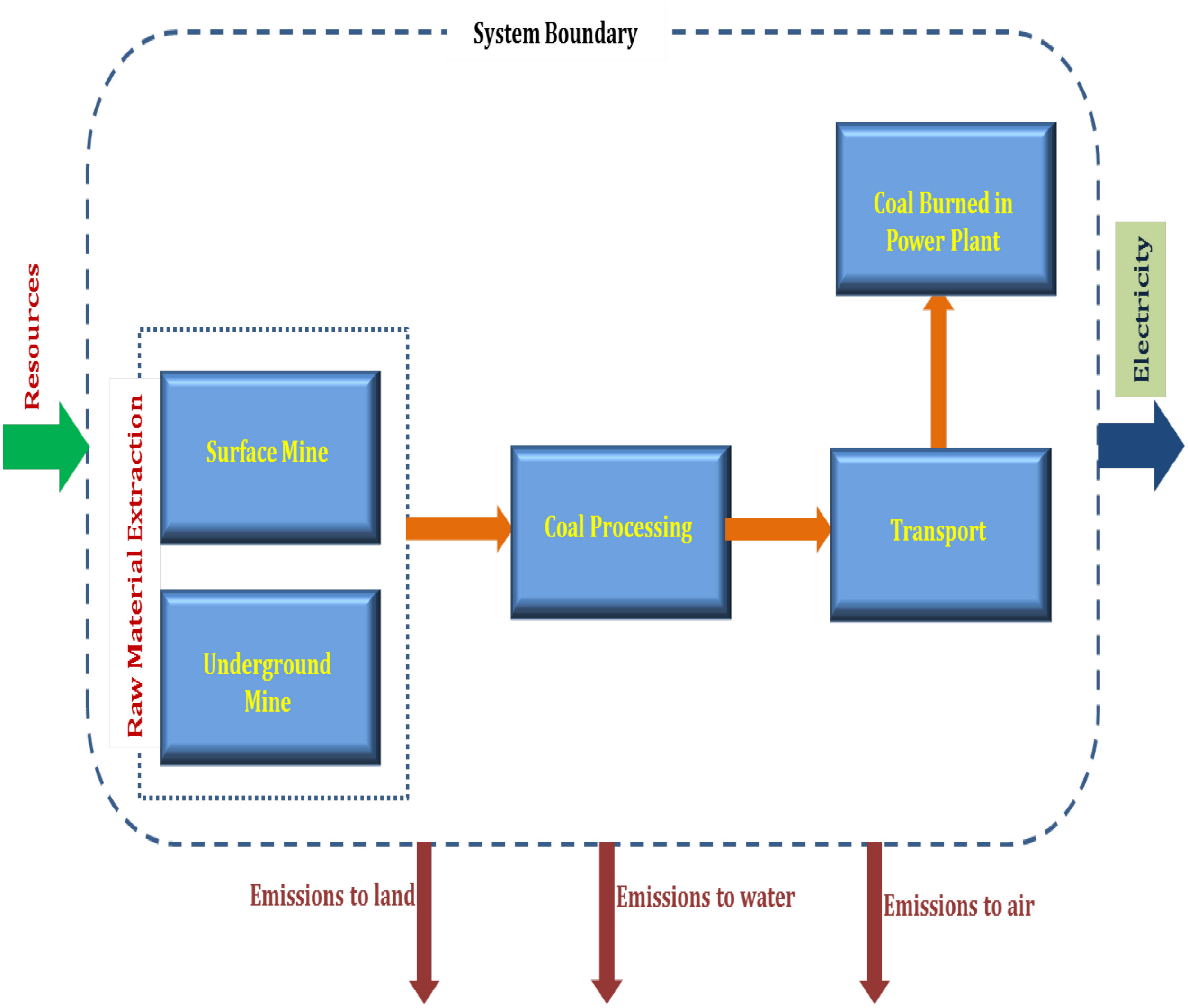


Figure 8.2: System boundary for coal

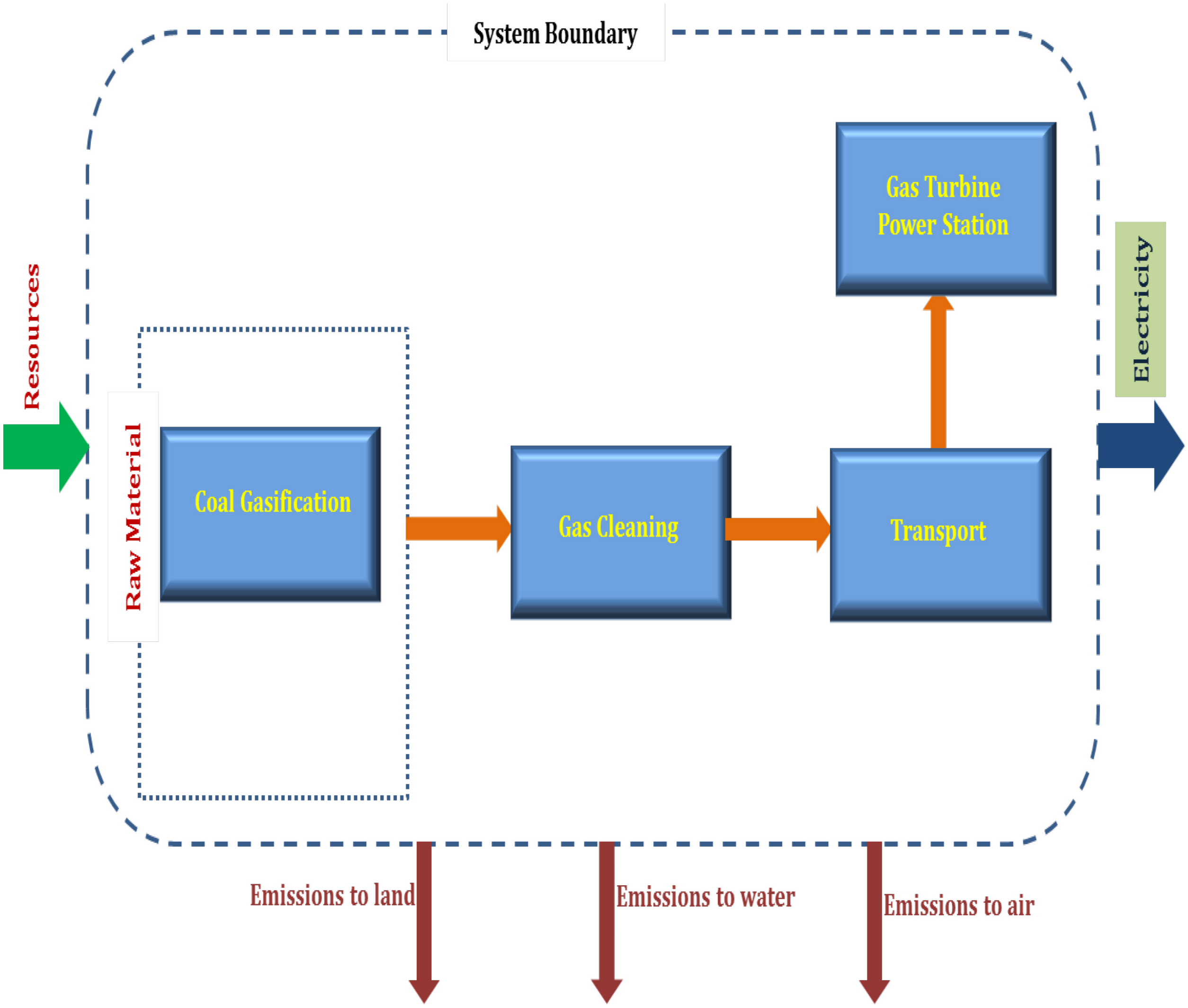


Figure 8.3: System boundary for UCG

8.6 Raw Material Extraction

For conventional PCC, SCPC and coal IGCC plants, the main raw material is coal extracted through mining. Statistical data shows that in the U.S. about 69% of coal is extracted through surface mining and about 31% is extracted through underground mining [NMA. 2011; Young 2011]. These statistics have been used in this study to get a weighted average estimate of emissions from mining coal in the U.S. The mining process generally involves three main stages namely extraction, material transport and handling, and beneficiation and processing [ITP 2007]. Each stage involves different equipment contributing to the overall energy consumption and environmental loads of mining activity. The electricity, diesel and gasoline consumption by these equipment is a significant source of GHG emissions from a mine [Ditsele and Awuah-Offei 2010]. The overall energy consumption by different equipment from a typical surface and underground coal mine is analyzed for establishing their contribution to the overall GHG emissions of the mining process.

8.6.1 Underground Mining

For the emissions from energy and equipment use of underground coal mining, the data from the Energy Efficiency and Renewable Energy's (EERE) hypothetical eastern U.S. underground coal mine is used [EERE 2002; ITP 2007]. The mining method used for this mine is room and pillar, with a 20-year mine life and 20 million ton output at the end of its life. The mine operates in two 9.00 hours shifts per day with 301 working days each year, giving an output of 3,322 tons per day. It is a bedded deposit with an average dip of 18 degrees and a 100 feet vertical distance to the surface. The energy requirement estimates for this hypothetical mine are based on the SHERPA Mine Cost Estimating Model and Mines and Mill Equipment Cost, an Estimator's Guide from Western Mining Engineering, Inc. to model the typical equipment requirement and the energy consumption for each major equipment [EERE 2002; ITP 2007]. The equipment and energy requirements for this mine based on EERE's data are calculated in Appendix A.

In addition to emissions from using the equipment, the fugitive methane emissions are also included in the total load of GHG emissions from mining.

8.6.2 Surface Mining

For emissions from energy and equipment use in the surface mining component, the data from Energy Efficiency and Renewable Energy's (EERE) hypothetical western U.S. surface coal mine is used [EERE 2002]. This surface mine has 20-years lifetime with a 200 million ton total coal production at the end of its life. The mine operates in two 10-hour shifts per day and runs for 360 days per year. Coal production for this mine is 27,778 tons per day and waste production is 114,243 tons per day. The ore travels a 1000 feet distance over a gradient of 8% and the waste travels a distance of 70 feet over a gradient of 8%. The equipment and energy requirements for this surface mine based on EERE's data are calculated in Appendix B.

8.6.3 UCG

For underground coal gasification, the data from the Chinchilla project from Australia is used. Chinchilla is located about 300 km west of Brisbane Australia. This was a pilot project involving construction of an underground gasifier and demonstration of gasification technology. The project used air as oxidizer, injected through the injection well into a 10-m thick coal seam at a depth of 140 m. The produced syngas had a heating value of 5.0 MJ/m^3 at a pressure of 10 bar$_g$ (145 psi$_g$) [Blinderman and Jones 2002]. The insitu generator developed for gasification had nine processing wells that produced 80,000 Nm^3/h of gas at maximum capacity. The temperature of gas was 300°C (570° F) and the project demonstrated 100% availability of gas production over a period of 30 months [Blinderman 2004]. The energy requirement, emissions and efficiency data for UCG has been taken from this project. The project demonstrated successfully the UCG-IGCC feasibility for electricity production and emissions were comparable or less than the emerging IGCC technologies [Blinderman 2004]. The project consumed 35,000 tons of coal and resulted in 80 million Nm^3 of syngas with a heating value lying between 4.5-5.7 MJ/m^3. The project demonstrated 95% coal resource recovery and coal to gas conversion efficiency of 75% [Shafirovich and Varma 2009]. Appendix C shows the energy and resource requirements for UCG.

8.7 Coal Cleaning and Processing

Coal cleaning and processing is an important step in the preparation of raw material before its use for the power generation. In this process, the impurities such as sulfur, ash and rocks are removed from the coal. The process involves communition, screening and sizing, classification and washing, dewatering and drying. As per 2011 Coal Age U.S. Prep Plant Census, there are 293 coal preparation plants in the U.S., this number was 286 in 2010 [Fiscor 2011] and 212 in the 2000 census [Fiscor 2000]. The average capacity of preparation plants in the U.S. is about 1000 tons per hour (TPH) [Vipperman, Bauer et al. 2007].

Emissions from the coal preparation plant include fugitive particulate matters, air exhaust from the separation processes, emissions from dry cleaning process where coal is stratified by pulses of air and coal combustion products including carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compound (VOC), sulfur dioxide (SO_2) and nitrogen oxides (NO_x) resulting from burning coal to generate hot gases [EPA. 1995].

For the emission of preparation plants, the assumption from the hypothetical Eastern underground Mine of EERE are used [EERE 2002]. The mine has a production rate of 3,322 tons per day and this run-of-mine material is fed to the preparation plant, thus requiring a prep plant of moderate capacity of 185 tons per hour. The energy consumed and equipment required for this plant is calculated in Appendix D.

8.8 Gas Cleaning and Processing

The composition of syngas depends upon the type of coal, coal characteristics, amount of sulfur in the coal, seam depth, pressure and type of oxidant used and amount of water or moisture present. Ash and heavy impurities remain in the underground cavity and do not come out with the gas. If the sulfur contents of coal are higher, then the gas will need further cleaning through desulfurization process. Similarly, the water vapors in the gas need to be removed and treated before utilization of gas in the turbine [Moorhouse, Huot et al. 2010]. This water can be used for cooling the raw gas in the heat exchanger. The gas need to be pressurized to the level suitable for use in the gas turbine, if the gas pressure is low or the coal seam is at shallower depth. The need of compressor is eliminated when the gasification is in the deeper seams [Blinderman and Jones 2002]. The energy requirement data for UCG is very scarce and no commercial UCG gas cleaning plants are setup. However, data for gas cleaning for surface gasifiers is available and utilized for this study.

8.9 Coal Transportation

In the U.S., rails have been the most frequent mode of domestic coal transportation [EIA. ; EIA. 2008]. In 2010, railroads transported about 70.2% of domestic coal, while trucks accounted for 11.7%, river for 11.2% (mainly barges on inland waterways) and tramway, conveyor and slurry pipelines accounted for 6.6% [EIA. 2011]. About 95% of coal is transported though highly productive unit trains which use dedicated equipment and operate round the clock [Association of American Railroads 2010]. In 2010, railroads originated 7.07 million carloads of coal carrying 814 million tons of coal with the average car carrying 115.3 tons and the average length of haul reaching 836 miles in 2009 [Association of American Railroads 2011].

In this study, coal transportation through railroad, trucks and barges is considered. The rails accounted for 75% of coal transportation while trucks and barges accounted for 15% and 10% respectively.

The average haul-distance for delivery of coal to the power plant is 836 miles, the average length of haul for the U.S. class-I freight rail transporting coal [Association of American Railroads 2011]. This distance comes to be 1632 miles for a round trip. The rail has 100 cars and 2 locomotives and delivers about 11,600 tons per trip, the U.S. average value is 64.2 tons per car load for class-I freight rail services in 2009 [DOT. 2011b], however, a typical coal train is 100 to 120 cars long with each hopper holding 100 to 115 tons of coal [University of Wyoming 2001]. Average diesel fuel consumption by the train is 0.14 miles per gallon [DOT. 2011a]. In 2011, U.S. freight railroads moved a ton of freight at an average of 469 miles per gallon of fuel [Association of American Railroads 2012].

Trucks transport 15% of coal to the power plant. The average payload of truck is 25 tons and the average fuel economy is 6.1 miles per gallon [Federal Railroad Administration 2009]. The truck travels a total distance of 200 miles round trip for coal delivery.

8.10 Gas Transportation

For gas transportation, the distribution network for natural gas is assumed, as there is no gas pipeline available solely for UCG. It is assumed that gas is transported through a distance of 300 mile via long distance natural gas pipeline. The emissions associated with the transportation of gas are those in the database of SimaPro software for the long distance, natural gas pipeline. The data includes emissions and energy requirement for the transport of average natural gas in the long distance gas transportation network using average compressor station. The data for emissions is from 1994 and for energy requirements is from 2001. Although this data is not completely representative of transport for UCG, this however gives a reasonable estimate for energy requirements and emissions.

8.11 Sources of Data Acquisition

This chapter used several sources for data including journal articles, government documents, published reports, conference papers, websites, government and other agencies databases and in build database of the SimaPro software.

For the coal component of this study, there are several excellent reports and papers dealing with the life cycle emissions of power generation from coal and provide an excellent source of data. The majority of these life cycle studies, compare the coal and natural gas power generation systems [Spath, Mann et al. 1999; Ruether, Ramezan et al. 2004; Jaramillo, Griffin et al. 2005; Jaramillo 2007; Jaramillo, Griffin et al. 2007; Dones, Bauer et al. 2008; PACE 2009; DiPietro 2010; Draucker, Bhander et al. 2010; Reddy 2010; Donnelly, Carias et al. 2011; Fulton, Mellquits et al. 2011; George, Alvarez et al. 2011; Hughes 2011; McIntyre, Berg et al. 2011; Skone 2011].

The government databases, reports and websites that provide useful data for this analysis include the U.S. Department of State, Department of Energy, Department of Transportation, National Energy Technology Laboratory, Environmental Protection Agency, Energy Information Administration, International Energy Agency and several others.

For the fugitive methane emissions, EPA provides very useful data for both coal mining and gasification processes [EPA. 2012].

For UCG, major data source is the Chinchilla project in Australia. Several papers, reports and evaluations provide data for this project. The gas transportation data is used from the built-in database of SimaPro.

8.12 Data Accuracy and Limitations

Since several sources are used for data collection, to ascertain the level of data accuracy is very difficult. The data collected from different reports, studies, databases and websites has varying levels of accuracy. The government databases provide reasonably accurate data and whenever was possible, were the primary sources of data. The peer reviewed papers and government reports are given preference for data collection. The database provided with the SimaPro software provides a good source for relatively accurate data. Careful consideration is given to get most accurate, representative and latest data. However, where accurate and up-to-date data is not available from primary sources, then second most relevant and accurate data source is used relaxing the geographical constraints. For example, in case of gasification, the accurate and up-to-date data for UCG projects in the U.S. is not available; therefore, data available for the Chinchilla project (the latest available source of UCG data) is used. Thus, the comparison of coal production and utilization in the U.S. power plants to the gas production and utilization in the Australia, though not very accurate and rational in the strict sense of geography and data consistency, provides a tolerable basis for analysis, without any hard conclusions.

The inherent data source uncertainties and variations in accuracy levels especially in case of UCG dictate that no strong conclusion are drawn from this analysis for small differences in the life cycle emissions. The results reported here are not for commercial utilizations or ecological claims. They provide the basic comparison for relative GHG impacts of different technologies and highlight the impacts of different stages for improvement in the methodology and technological alternatives.

8.13 Models

Following four cases are modeled in the SimaPro for analysis.

8.13.1 Pulverized Coal Combustion (PCC) Plants

The pulverized coal combustion system is the basic method for thermal power generation. In this method, coal is first ground to very fine powder and this powder is then ignited to produce energy. This energy is then utilized to generate steam that runs the large turbines for electricity generation. The average plant consists of pulverized coal boilers, baghouse filter, flue gas cleanup system, heat recovery steam generators and steam turbines [Spath, Mann et al. 1999]. NO_x emission and unburned carbon are most problematic pollutants for this system [Kurose, Makino et al. 2003]. Figure 8.4 shows the general processes involved in the life cycle of a coal-fired power plant.

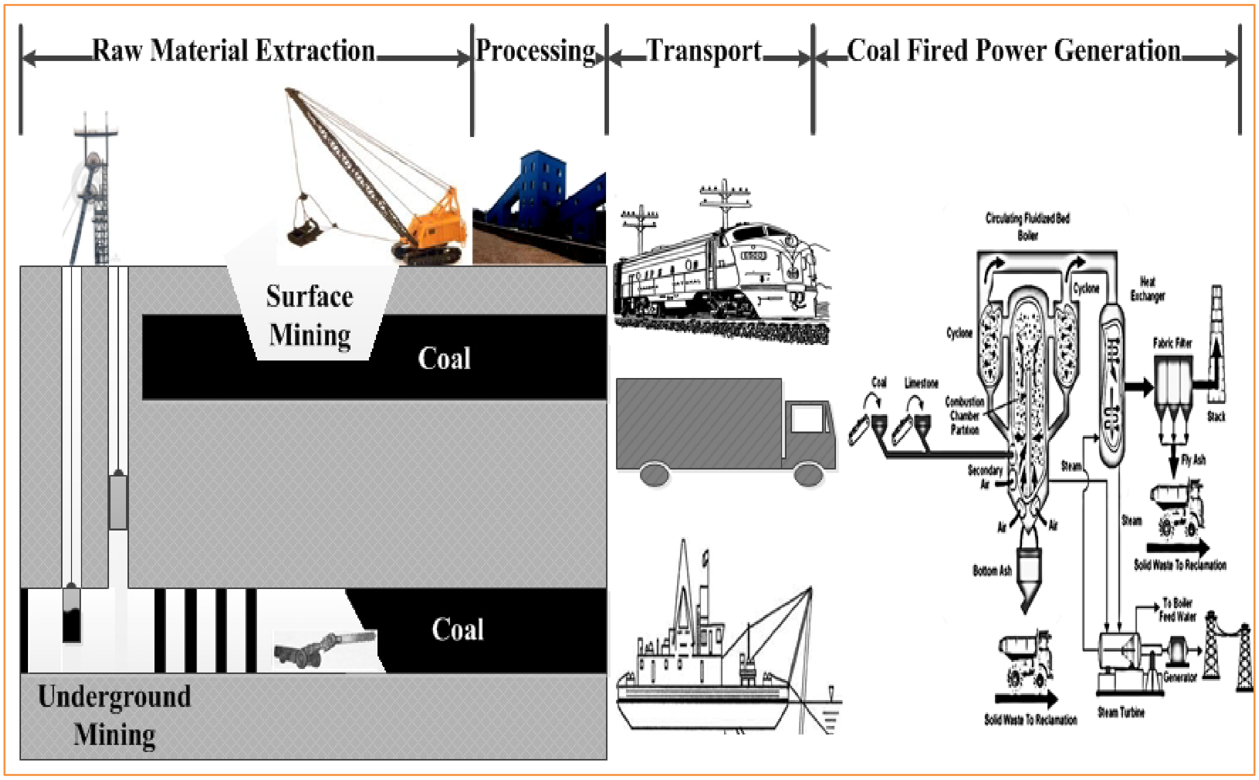


Figure 8.4: Coal's life cycle

The plant efficiency is representative of the average efficiency of all the plants in this category in the U.S. Coal consumption for the plant is calculated based on the heating value of coal, plant efficiency, plant availability and coal losses during transportation. Table 8.1 shows the data used for the PCC plant.

Table 8.1: Data used for PCC plant

Data for PCC Plant	
Calorific value of coal	26.4 MJ/kg
Plant efficiency	32%
Plant Capacity	425 MW
Operating capacity factor	60%
Coal haul losses	5%
1 ton	1000kg

1 year	365 days
1 day	24 hours
1 hour	3600 seconds
MJ/kg	238.8 kcal/kg
Coal requirement	999,643 ton /year
Rail transport distance	836 miles
Truck transport distance	200 miles
Barge distance	250 miles
Rail load	749,732 tons/year
Truck load	99,964 tons/year
Barge load	149,946 tons/year

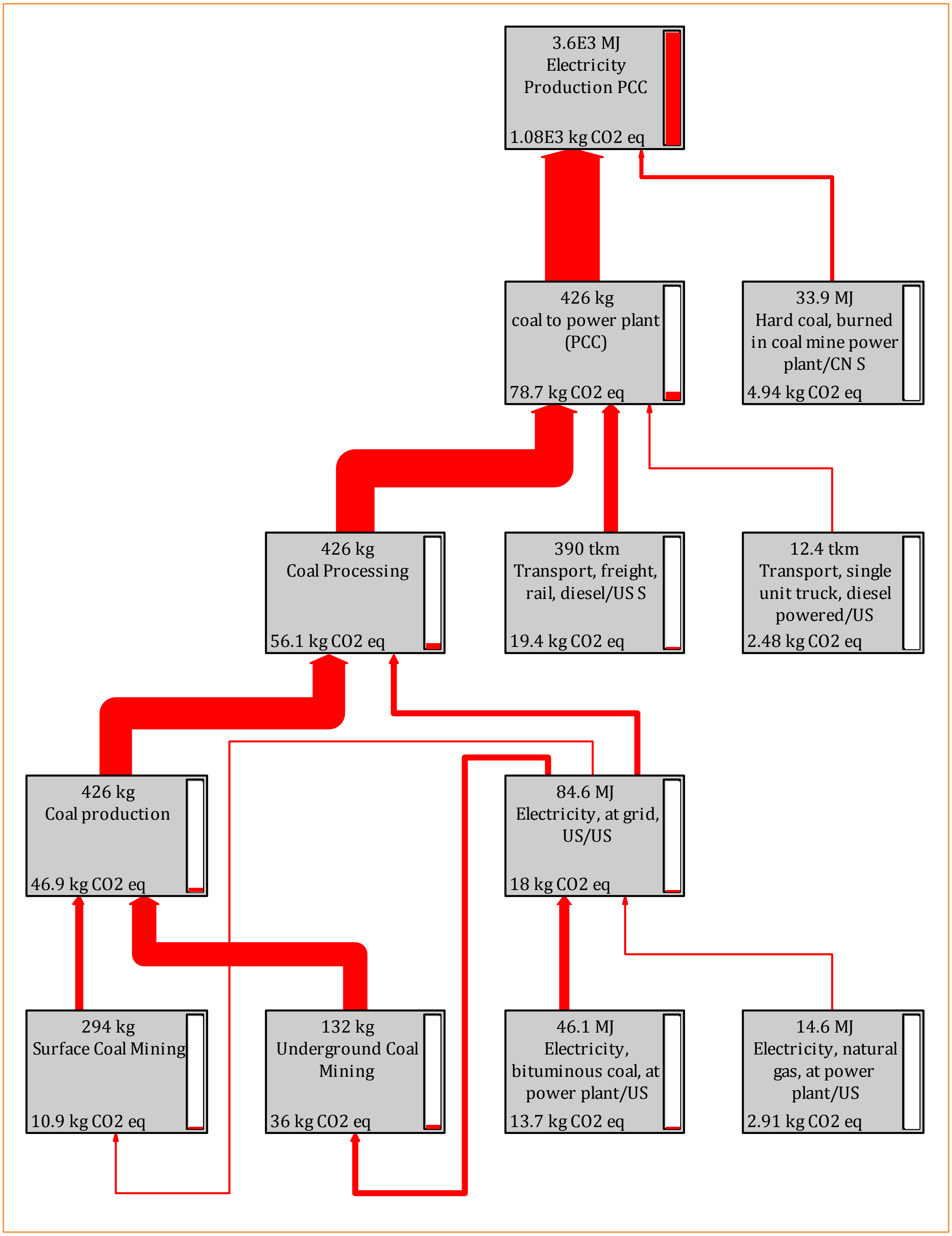


Figure 8.5: Complete life cycle model of PCC plant

Figure 8.5 shows the life cycle model for the PCC plant. The major contribution is from coal mining, processing, transportation and electricity generation. This model is formed by the combination of different components of life cycle to get the emission for 1MWh of electricity generation. The models for contributing components of life cycle are attached as Appendix E, Appendix F and Appendix G. The complete model is composed of 74 products, 66 processes, 186 links and 54 nodes, out of which only 12 nodes are displayed here for brevity. The complete model showing all 54 nodes is attached as Appendix H.

8.13.2 <u>Supercritical Pulverized Combustion (SCPC) Plants</u>

The supercritical pulverized coal power plants work at higher temperature and pressures. The steam temperature and pressure is raised considerably resulting in higher efficiencies and lower overall emission from power plant [Nalbandian 2009]. The CO_2 emissions are at reduced levels as compared to subcritical power plants. Supercritical is the thermodynamic expression for the homogeneous fluid, a state where there is no distinction between gaseous and liquid phase [Power 4 Gerogians 2008]. These plants operate above a temperature of 1075 °F (~ 580 °C) and at an operating pressure of above 22.1 MPa [Power 4 Gerogians 2008]. Table 8.2 shows the data used for SCPC plant.

Table 8.2: Data used for SCPC plant

Data for SCPC Plant	
Calorific value of coal	26.4 MJ/kg
Plant efficiency	38%
Plant Capacity	400 MW
Operating capacity factor	60%
Coal haul losses	5%
MJ/kg	238.8 kcal/kg
Coal requirement	792,287 tons /year
Rail transport distance	836 miles

Truck transport distance	200 miles
Barge distance	250 miles
Rail load	594,215 tons/year
Truck load	79,229 tons/year
Barge load	118,843 tons/year

Figure 8.6 shows the life cycle model for SCPC plant. Major components contributing in the life cycle emissions are shown. The model shows GHG emissions in kgCO_2e per MWh of electricity generated. The model shows only 12 nodes out of 54 nodes. The components contributing to the complete model are shown at Appendix E, Appendix F and Appendix G and the complete model is shown at Appendix I.

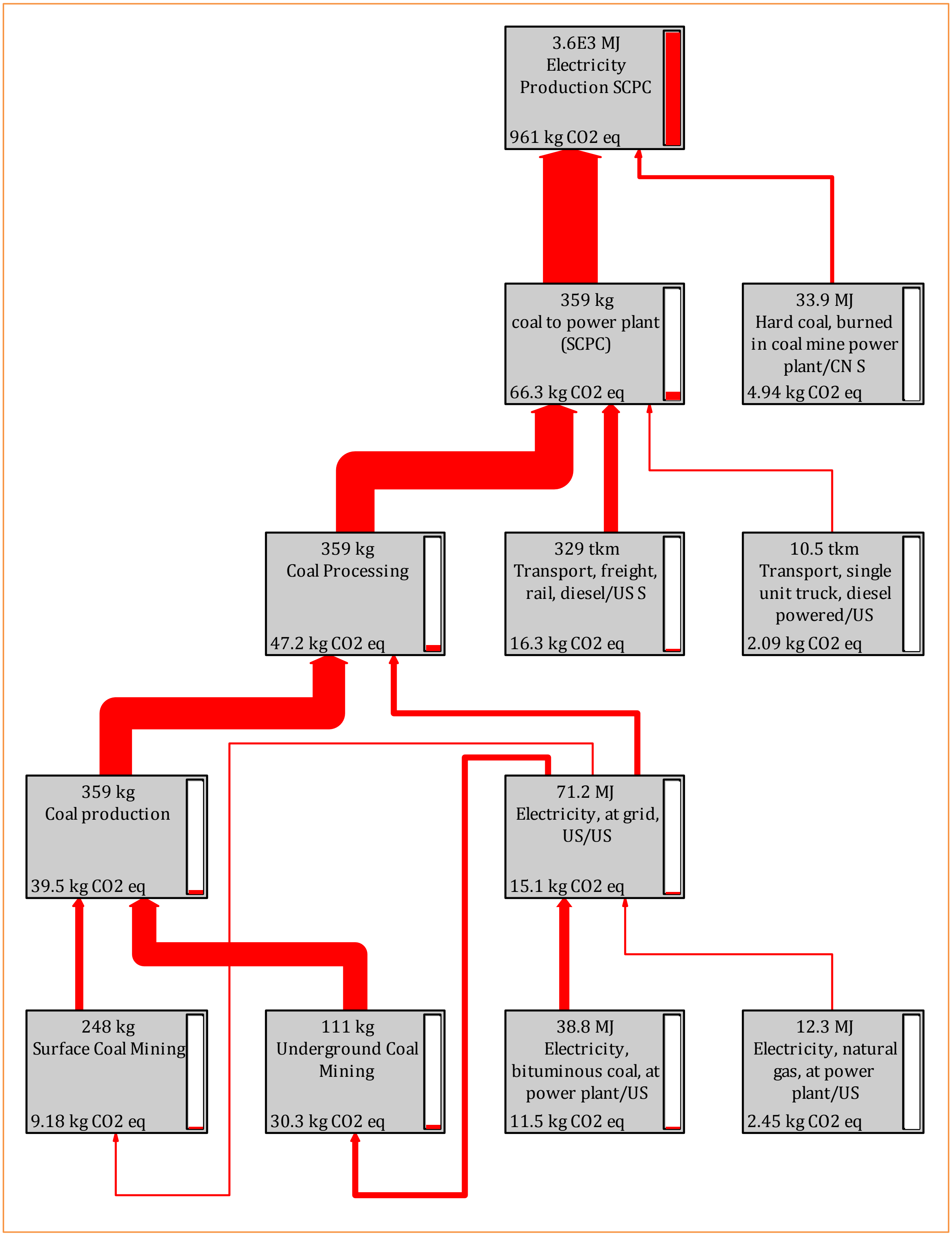


Figure 8.6: Complete life cycle model of SCPC plant

8.13.3 Integrated Gasification Combined Cycle (Coal-IGCC) Plants

In the IGCC plants, coal is first converted into a gaseous product through a surface gasifier. This gas is then purified and combusted for electricity generation in a combined cycle turbine. Gas cleaning allows removing the SO_x and NO_x impurities thus reducing their emissions load. Waste heat from the turbine is used to drive a steam turbine through a combined cycle system. The combined cycle improves the overall efficiency of the system. Typical efficiencies for IGCC are in the mid 40's, however efficiencies around 50% are achievable [WCA. 2012]. For this analysis, a higher efficiency for the IGCC plant is used so that the comparison can be made between the efficient IGCC plants and UCG-IGCC. Table 8.3 shows the data used for coal IGCC plant.

Table 8.3: Data used for Coal-IGCC plant

Data for Coal-IGCC Plant	
Calorific value of coal	26.4 MJ/kg
Plant efficiency	42%
Plant Capacity	425 MW
Operating capacity factor	60%
Coal haul losses	5%
MJ/kg	238.8 kcal/kg
Coal requirement	761,632 tons /year
Rail transport distance	836 miles
Truck transport distance	200 miles
Barge distance	250 miles
Rail load	571,225 ton/year
Truck load	76,163 ton/year
Barge load	114,245 ton/year

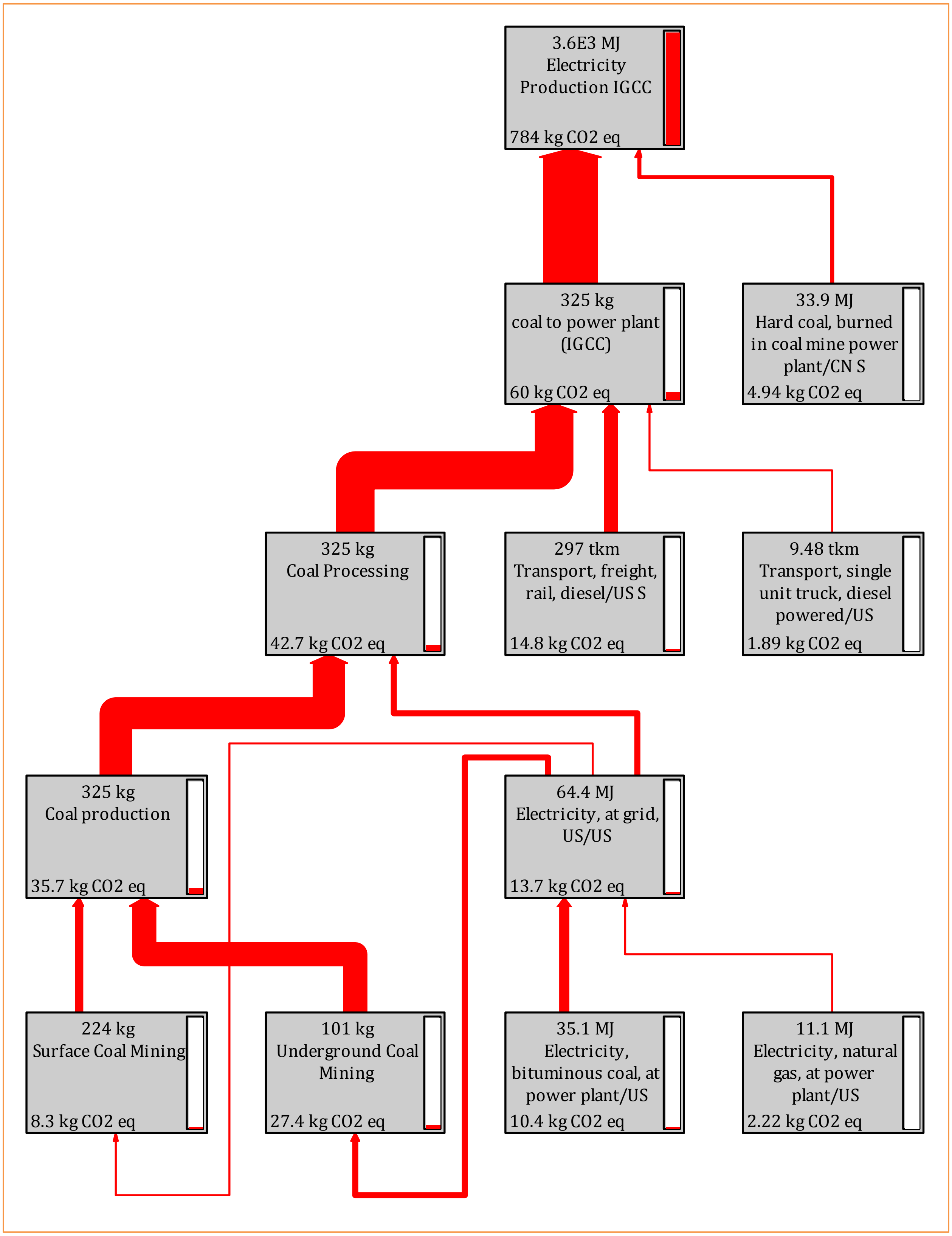


Figure 8.7: Complete life cycle model of Coal-IGCC plant

Figure 8.7 shows the life cycle model for coal-IGCC plant. The contributing components of model and complete model are shown at Appendix E, Appendix F, Appendix G, and Appendix J. The model shows the life cycle GHG emissions for 1MWh electricity production using IPCC 2007 estimates for GHGs for a 100-year timeframe.

8.13.4 <u>Integrated Gasification Combined Cycle (UCG-IGCC) Plants</u>

UCG-IGCC plants work similar to coal IGCC plants with the exception that instead of transporting coal to the plant and converting it into syngas, the coal is burned insitu and resulting syngas is transported to the power plant for use in a turbine to generate electricity. This eliminates the coal extraction portion of the cycle and reduces cost and emissions significantly. The gas can be cleaned prior to combustion and CO_2 can be captured from the syngas stream, further reducing the emissions load. This also runs in the combined cycle, utilizing the waste heat from the turbine to generate steam for use in the steam turbine. This increases the output and efficiency of the system. Figure 8.8 shows the complete cycle of power generation from UCG.

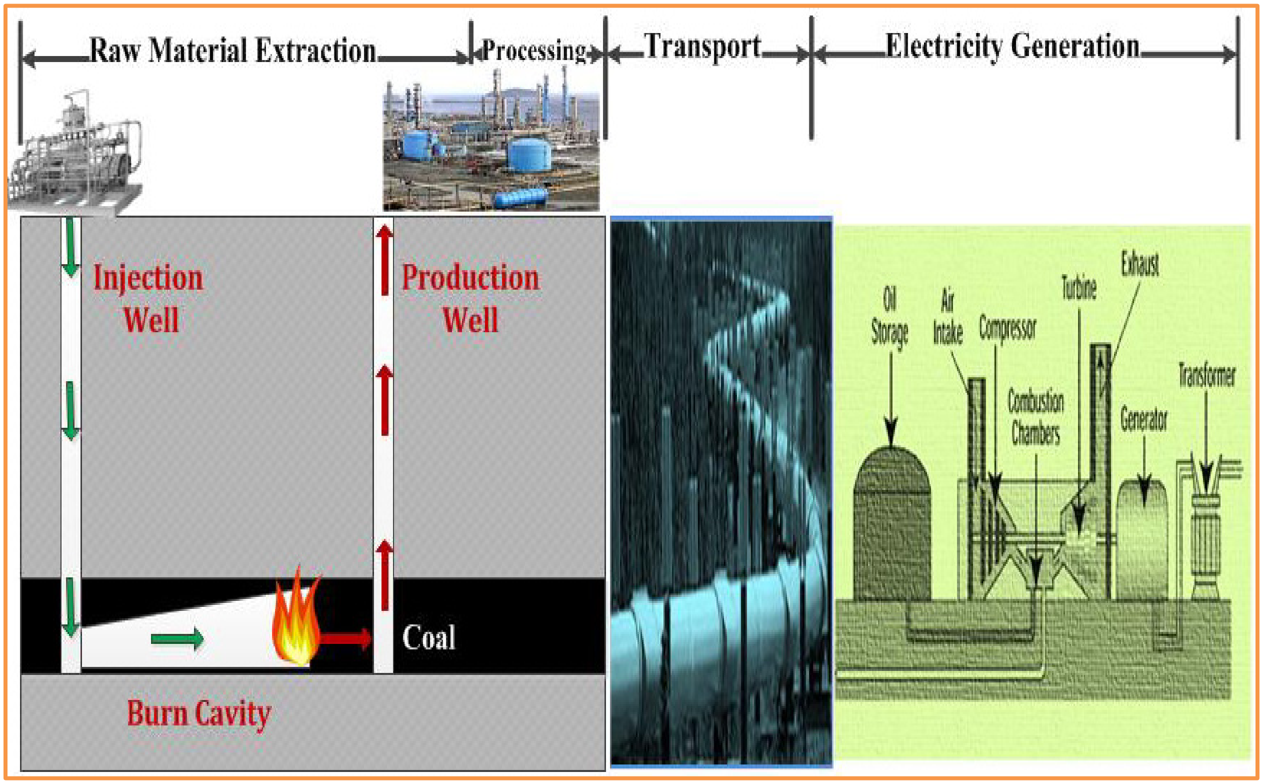


Figure 8.8: UCG life cycle

Table 8.4 shows the energy and materials used for UCG-IGCC Plant.

Table 8.4: Data used for UCG-IGCC plant

Data for UCG-IGCC Plant	
Calorific value of coal	26.4 MJ/kg
Calorific value of Gas	5.0 MJ/m^3
Turbine efficiency	50%
Plant Capacity	300 MW
Operating capacity factor	80%
Coal resource recovery	75%
Total plant life	20 years
Coal requirement	1, 650,000 ton /year
Gas requirements	3,784,320,000 m^3/year
Water	2.33 x 10^6 m^3/year
Copper ore (for wiring, generators)	234 ton/year
Oil	4,467.60 GJ/year
UCG electrical consumption	8.47 MW

The syngas is largely composed of CO_2, CO, CH_4, H_2, H_2S and some other gases in trace amounts. The composition of syngas varies from site to site depending on varying site and operational characteristics. Table 8.5 shows some common syngas compositions reported by different sources [Shafirovich and Varma 2009; Ag Mohamed, Batto et al. 2011].

Table 8.5: Syngas compositions

Chemical compositions of syngas				
	Spanish Trial 1st Test	Spanish Trial 2nd test	US trial	Indiana Study
CO_2 %	43.4	39.4	34.9	46.1
CO %	8.7	15.6	20.8	19.15
CH_4 %	14.3	12.4	4.7	9.43
H_2 %	24.9	24.7	38.1	24.31
H_2S %	8.3	8.8	1.5	0.69
Molar weight (g/mole)	27.14	30.174	27.204	27.8756

Figure 8.9 shows the life cycle model for UCG-IGCC. The emissions are based on IPCC 2007 method. The model computes GHG emissions for 1MWh electricity generation and consists of 59 products, 51 processes, 168 links and 51 nodes. The components of model contributing to life cycle and complete model showing all nodes and links and are attached as Appendix K, Appendix L and Appendix M.

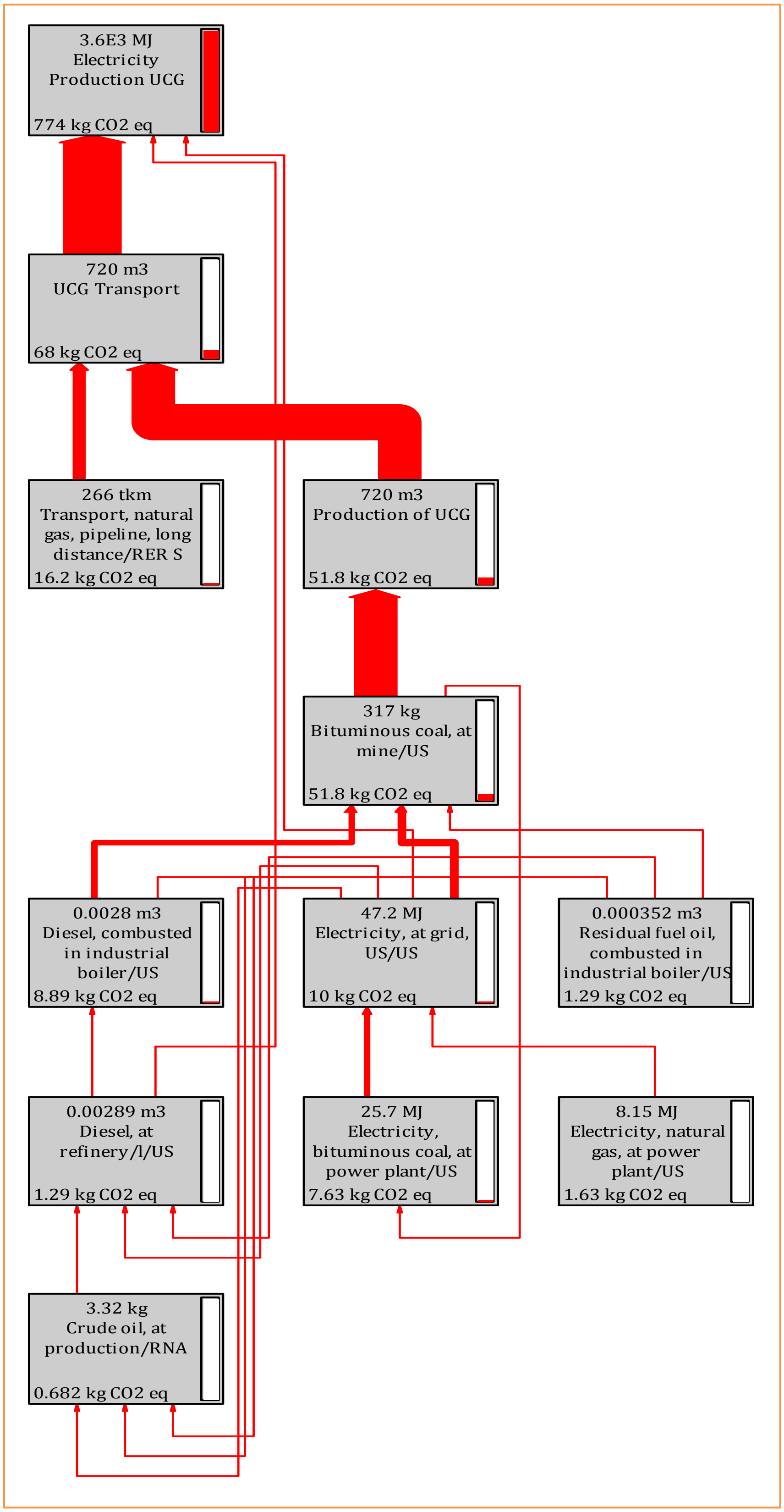


Figure 8.9: Complete life cycle model of UCG-IGCC plant

8.14 Inventory of Inputs and Outputs

The material and energy inputs for all the processes involved in the four scenarios (PCC, SCPC, IGCC and UCG-IGCC) are listed in Table 8.1, Table 8.2, Table 8.3, Table 8.4 and Appendix A, Appendix B, Appendix C and Appendix D. The inventory of emissions for all four cases is combined in Appendix Z . This table shows a complete list of more than 800 substances and materials used during these processes. The software has listed these substances based on the inputs and processes involved in the life cycle of all four cases. These are further categorized into emissions to air, water and soil and raw materials extraction. These substances are calculated for 1.0 MWh of electricity production by these generation technologies and the method used for categorization is based on 2007 IPCC definition of GWP for 100-year or "IPCC 2007 GWP 100a V1.02".

8.15 Results

The greenhouse gas emissions during different parts of life cycle are listed in Table 8.6. The emissions are measured in kgCO_2equivalent per MWh of electricity generated through each plant. The values used for this calculation are based on 2007 IPCC estimates for GHGs on a 100-year basis.

Table 8.6: Life Cycle GHG Emissions

Life Cycle GHG Emissions for Power Generation kgCO_2 e /MWh					
	Mining/Gasification	Cleaning/Processing	Transport	Electricity Generation	Total
PCC	46.9	9.2	22.6	1001.3	1080
SCPC	39.5	7.7	19.1	894.7	961
Coal-IGCC	35.7	12	17.3	719	784
UCG-IGCC	36.2	15.6	16.2	706	774

Table 8.6 shows that majority of GHG emissions are from the utilization of coal and gas in the power plant. The gas-cleaning portion of both IGCCs contributes considerable portion

of GHG emissions. The byproducts generated during this phase can be utilized for production of other chemicals but are not included or credited in this analysis; because such data has not been included about other power generation options. More than 90% of the emissions are from electricity generation in the power plants. Although, there is a great advancement in the technologies that curtail the GHG emission from power plants, there is a continued need of research in this area.

Table 8.6 also shows that the emerging or latest technologies have considerable achievements in reducing the GHG emissions in almost every aspect of electricity generation life cycle. UCG is very comparable to these latest technologies and in fact, the GHG emissions from UCG are about 28% less than the conventional PCC plant. When combined with the economic superiority, UCG has a clear advantage over competing technologies. Figure 8.10 shows the percent reduction in the GHG emissions when taking PCC as a base case. The comparison shows that there is considerable reduction in the GHG emissions with the development of technology and improvements in generation efficiencies.

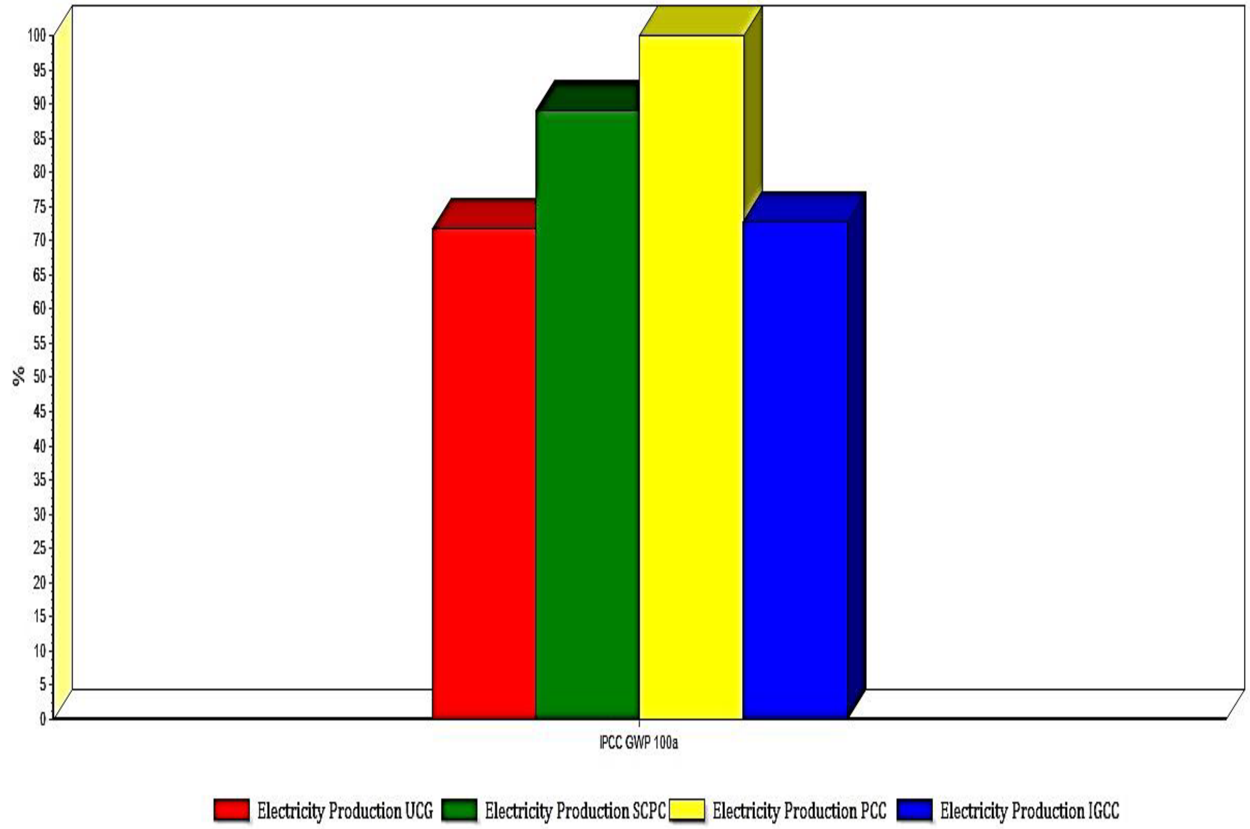


Figure 8.10: Comparison of percent GHG emissions with PCC as base case

Figure 8.11 shows the total life cycle GHG emissions for different generation technologies. The coal and UCG IGCC are almost equal in total GHG emissions; however, for this analysis higher efficiency for coal-IGCC was used. No carbon capture was taken into account for any technology. Carbon capture though reduces carbon emission from combustion of syngas, decrease the efficiency of IGCC plants. Figure 8.12 shows the contribution by different components of life cycle in the total GHG emissions. The emissions are presented in kgCO$_2$equivalent/MWh of electricity generation. Electricity generation is the major contributor in the total GHG emissions load of life cycle. Figures 8.13 to 8.16 show the contribution of various substances in the total GHG load for 1MWh electricity generation in each plant. It is clear from these figures that major contributor for GHG is CO$_2$ itself, followed by methane. Other GHG gases are in trace amounts. The method used for this characterization is based on 2007 IPCC estimates for global warming potential of GHGs based on a 100-year timeframe.

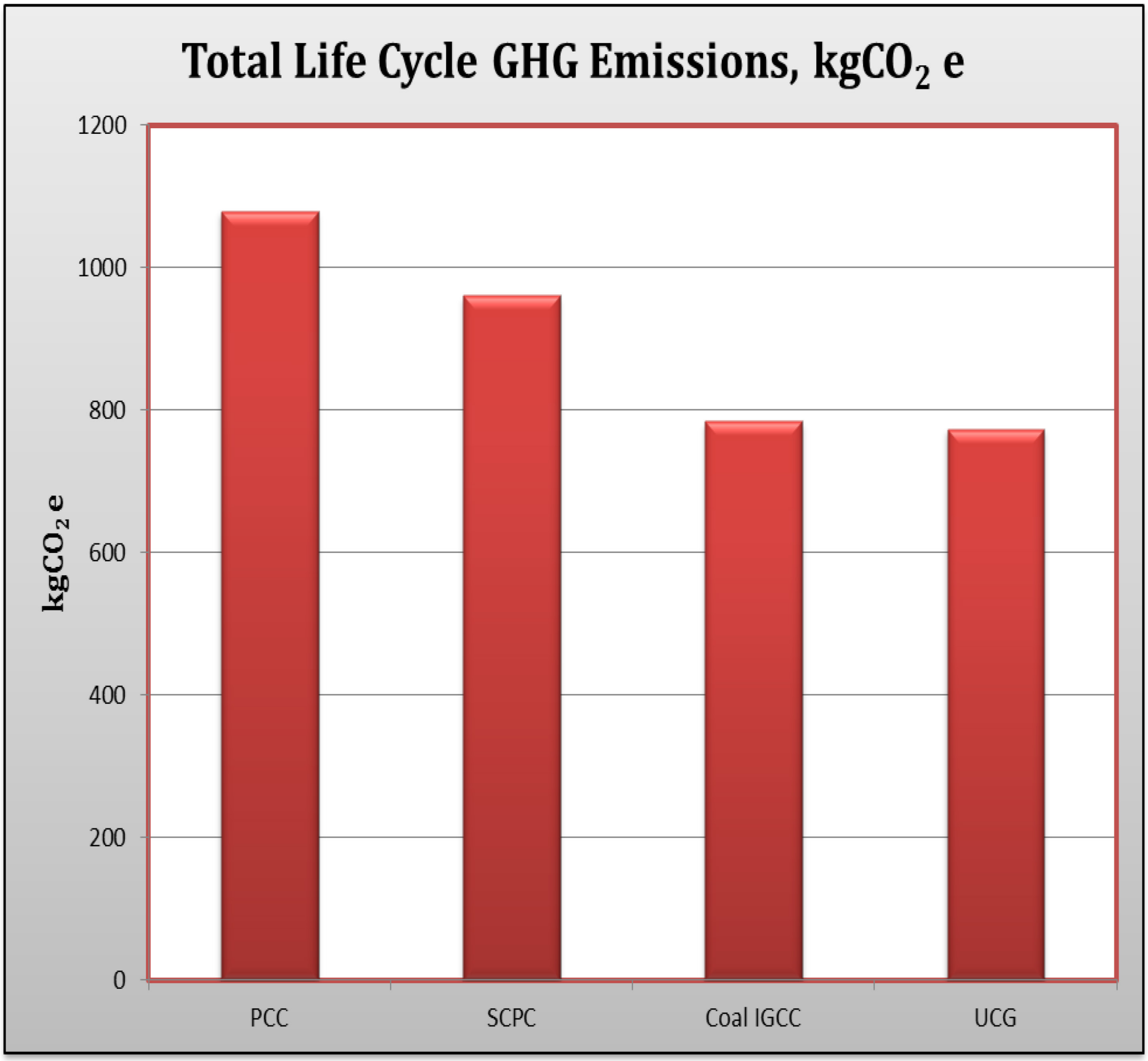


Figure 8.11: GHG emissions for different technologies

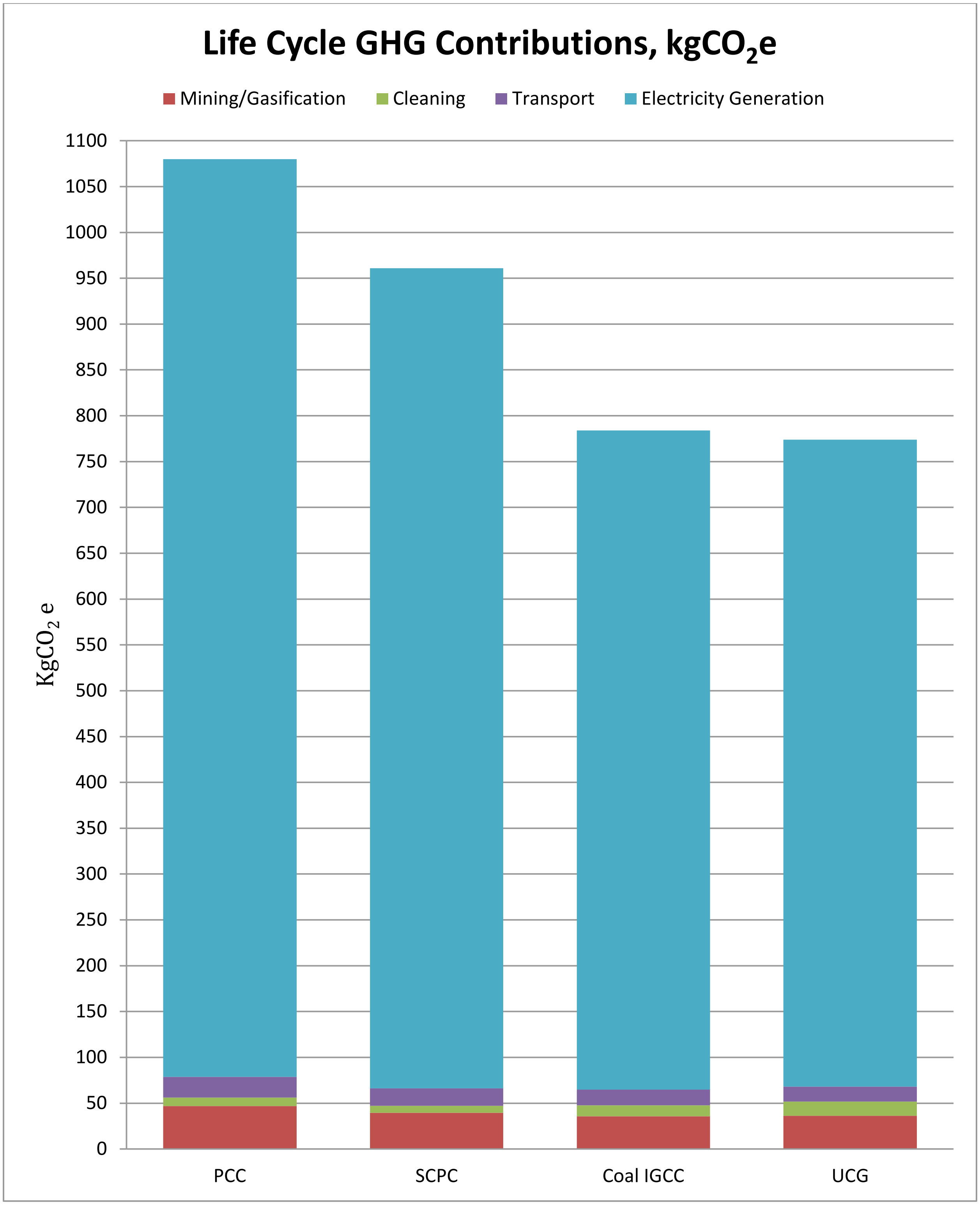


Figure 8.12: GHG contributions by different components of life cycle

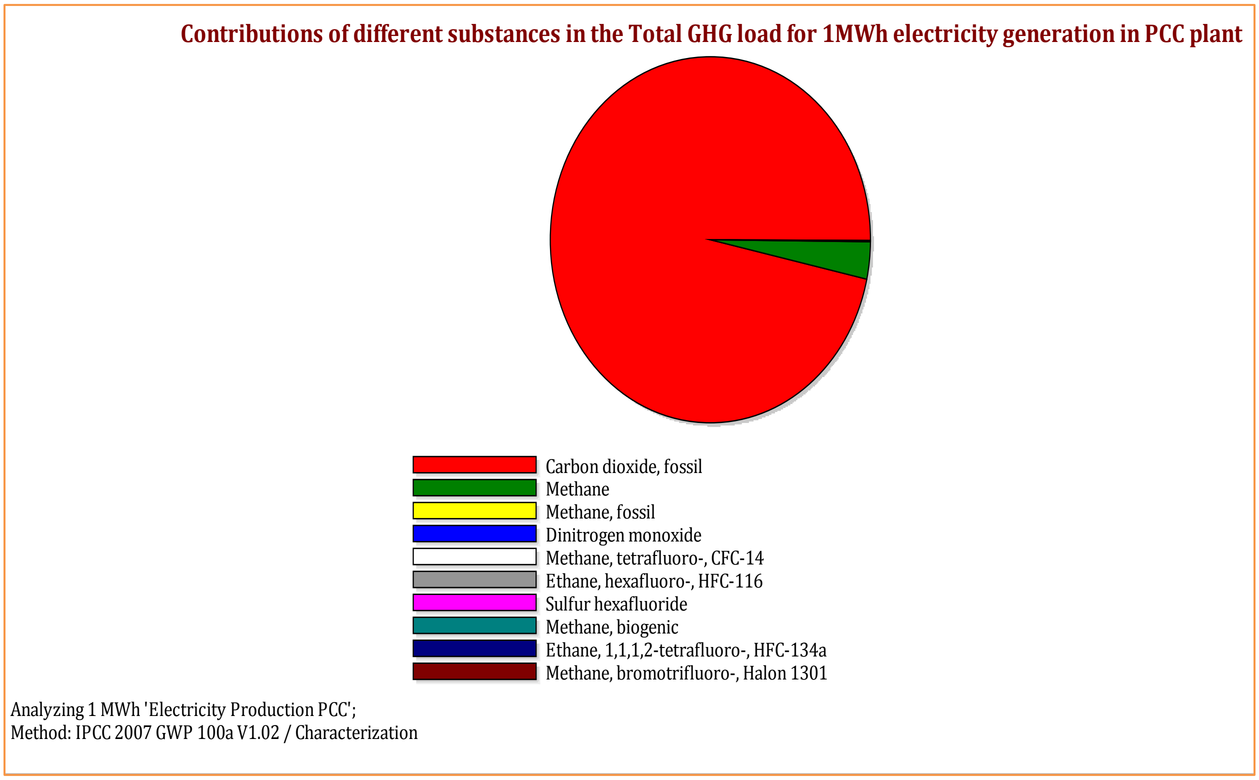


Figure 8.13: Contributions of different substances in the total GHG load for 1MWh electricity generation in PCC plant

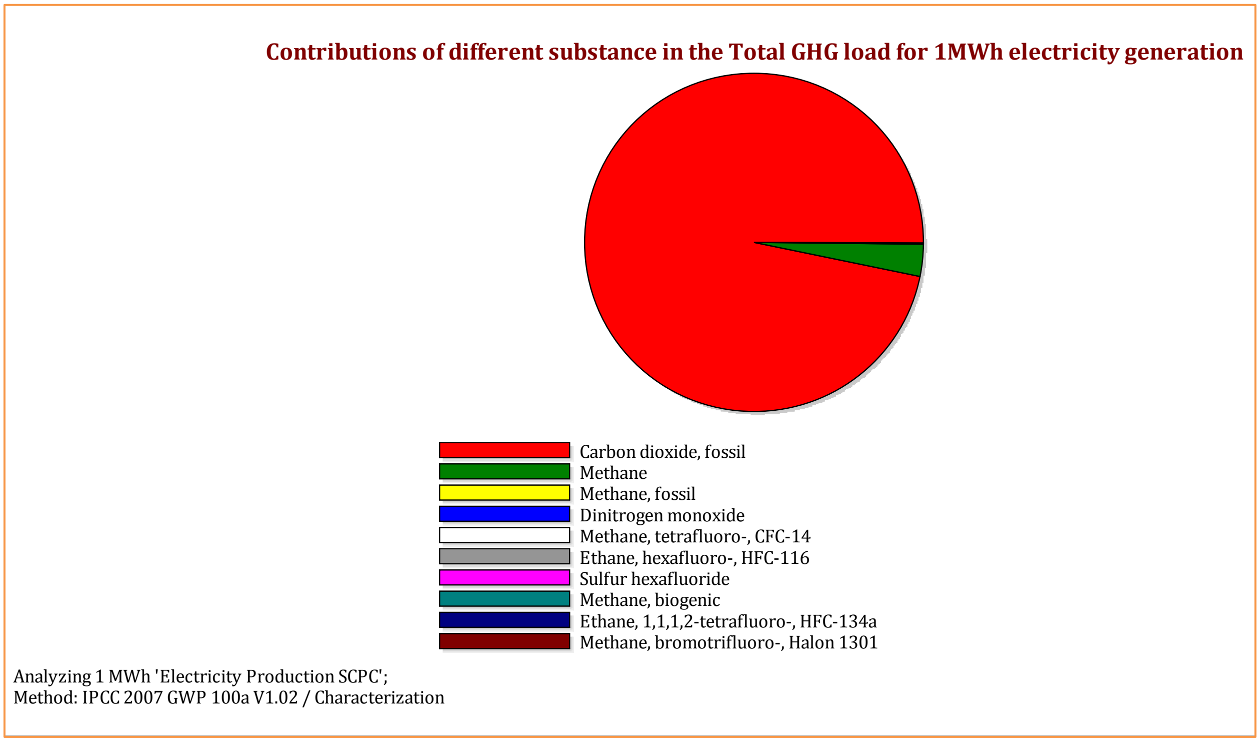


Figure 8.14: Contributions of different substance in the total GHG load for 1MWh electricity generation in SCPC plant

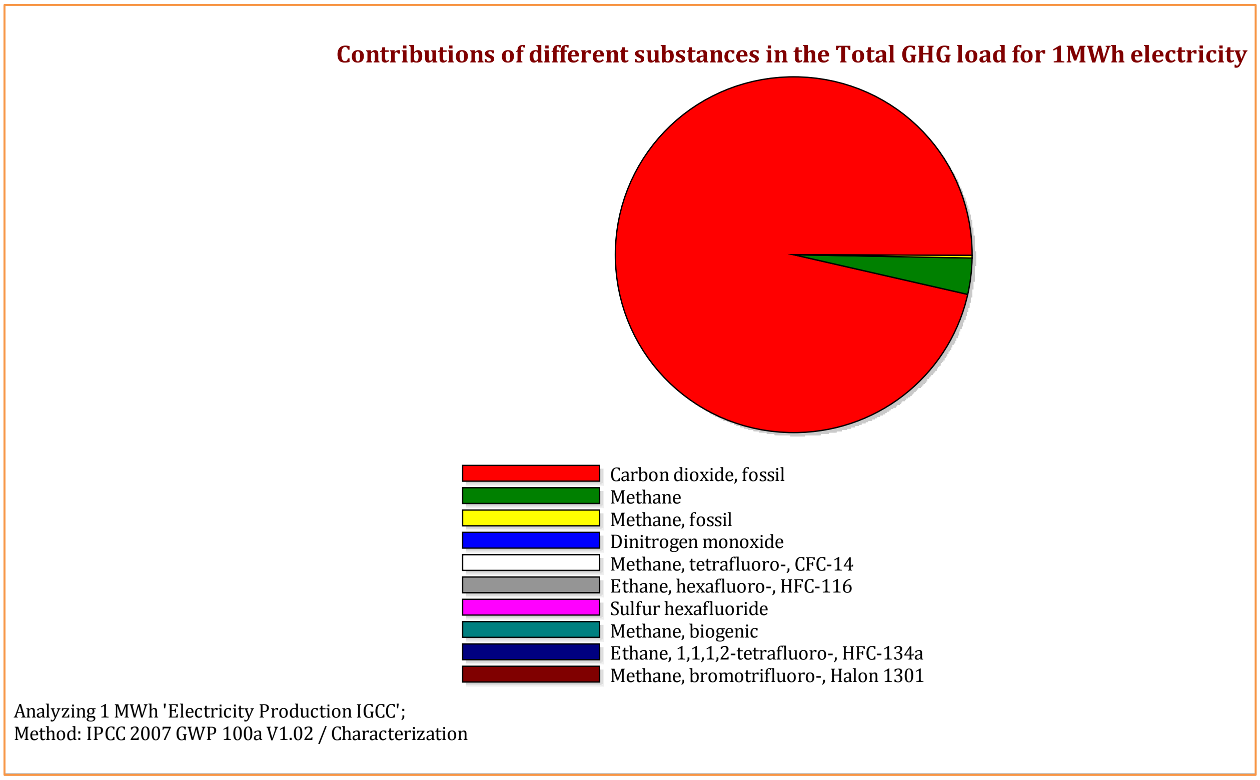


Figure 8.15: Contributions of different substances in the total GHG load for 1MWh electricity generation in Coal-IGCC plant

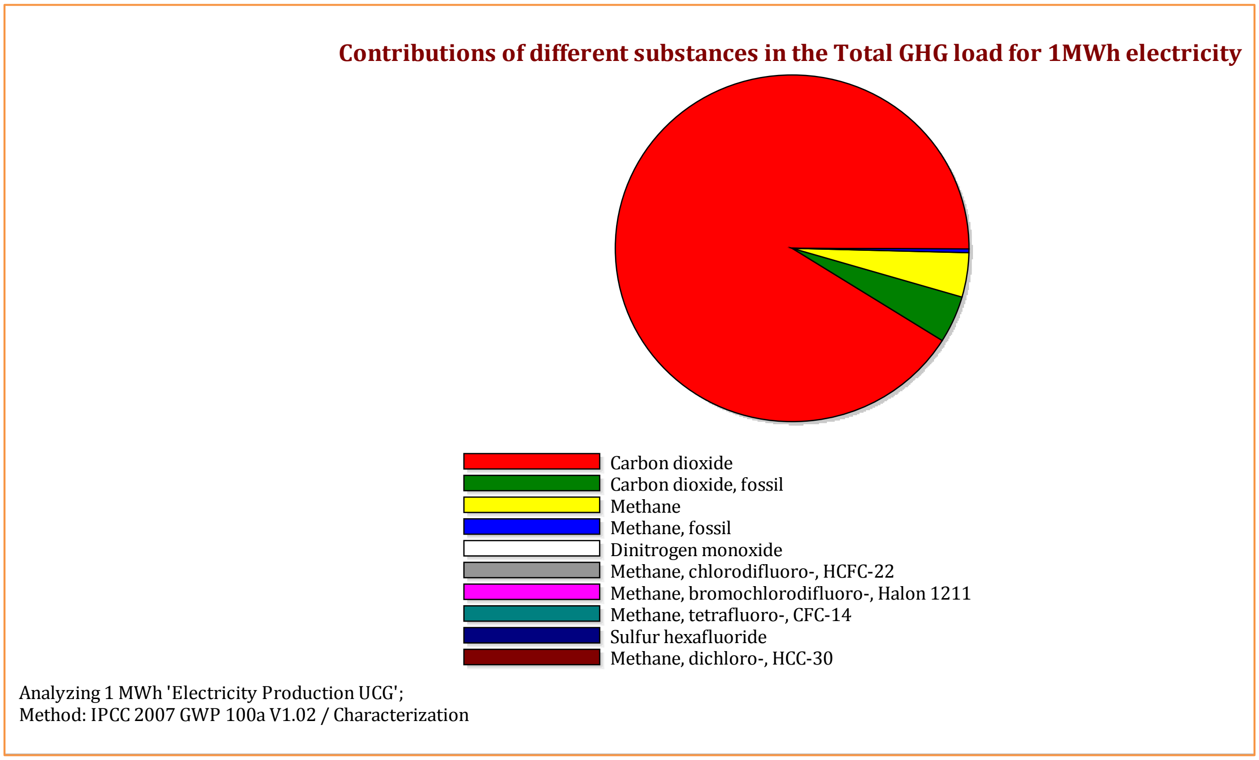


Figure 8.16: Contributions of different substances in the total GHG load for 1MWh electricity generation in UCG-IGCC plant

Several methods are used for characterization of environmental impacts per category in addition to IPCC method based on GWP. For example, Figure 8.17 shows the characterization of impact categories based on the eco-indicator method of 1999. This method has three damage categories, human health, ecosystem quality and resources [Pre Consultants 2010]. The software has the latest version of this method updated in July 2010. The environmental impact sub-categories in this method include carcinogens, respiratory organics and in organics, climate change, ozone layer depletion potential, Eco toxicity, land use, raw material extraction (minerals) and fossil fuels. UCG has higher impacts on the environment in the categories of carcinogens, respiratory inorganics, ozone layer depletions and mineral use, whereas its impacts are comparatively less in the respirator organics, climate change, radiation, land use, acidification/eutrophication and fossil fuel consumptions. Figures 8.18 to 8.21 show the contribution of different substances in the characterization of an impact category. In these figures, the example of carcinogens has been used to see the contribution of various substances in this environmental/human health impact for all generation processes. The environmental impact assessments of these electricity generation technologies based on various methods are shown in Appendix N to Appendix Y.

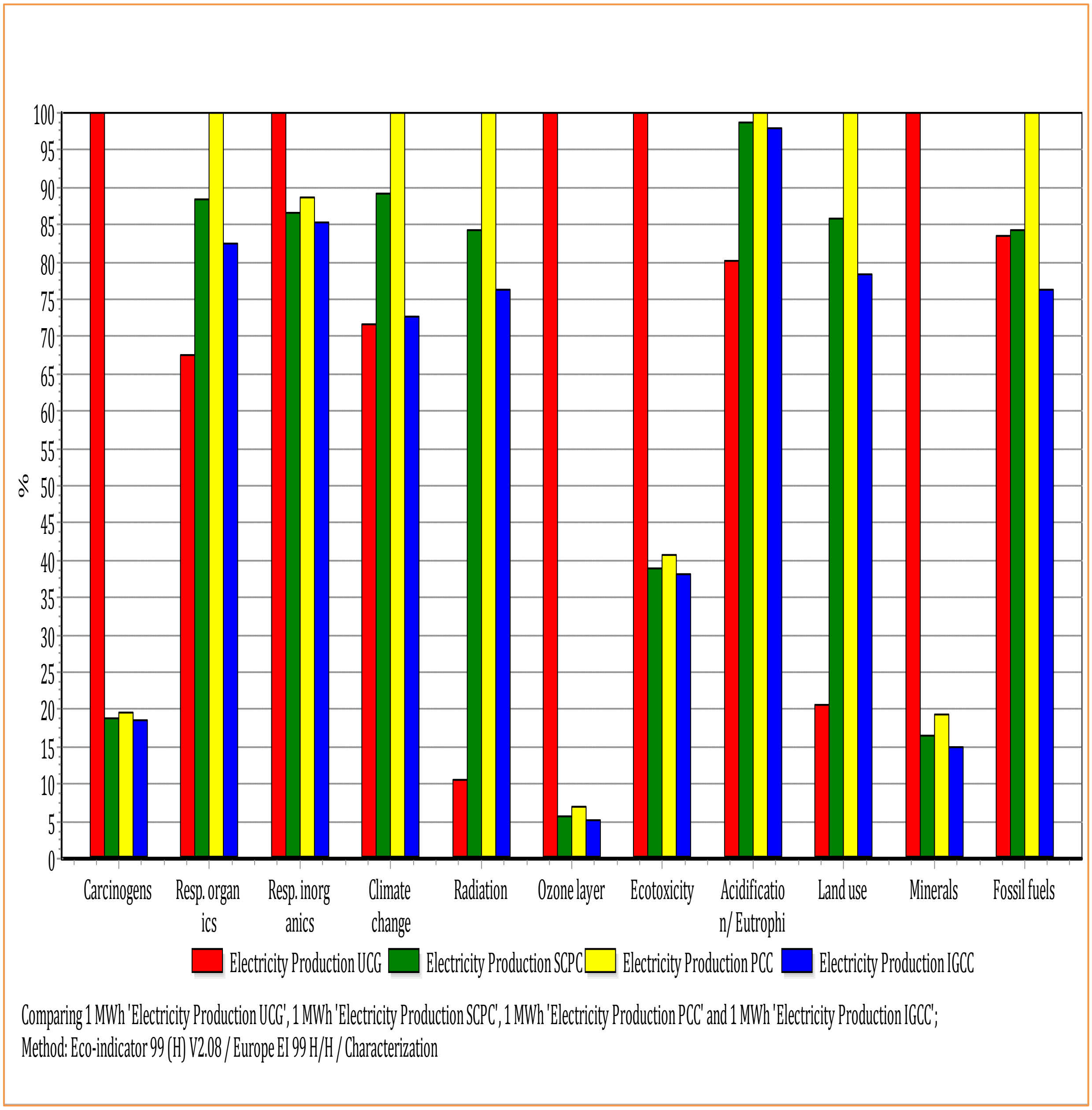
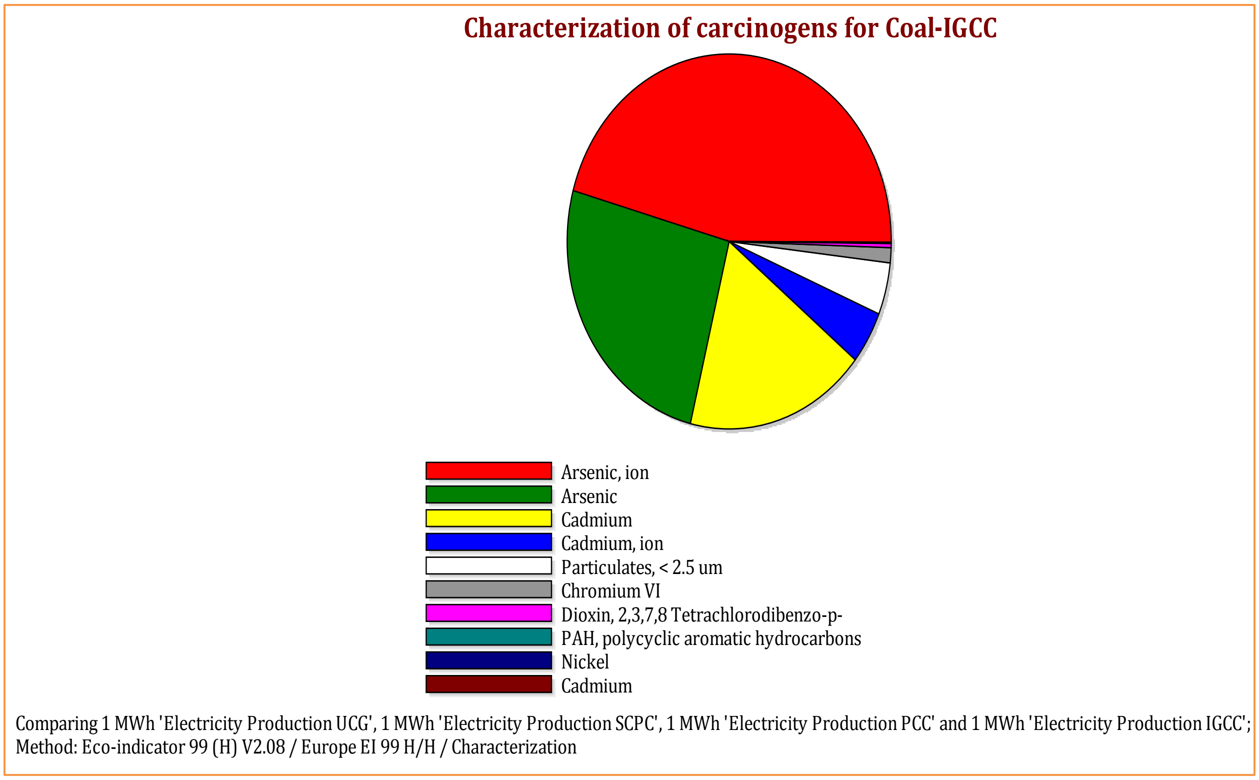
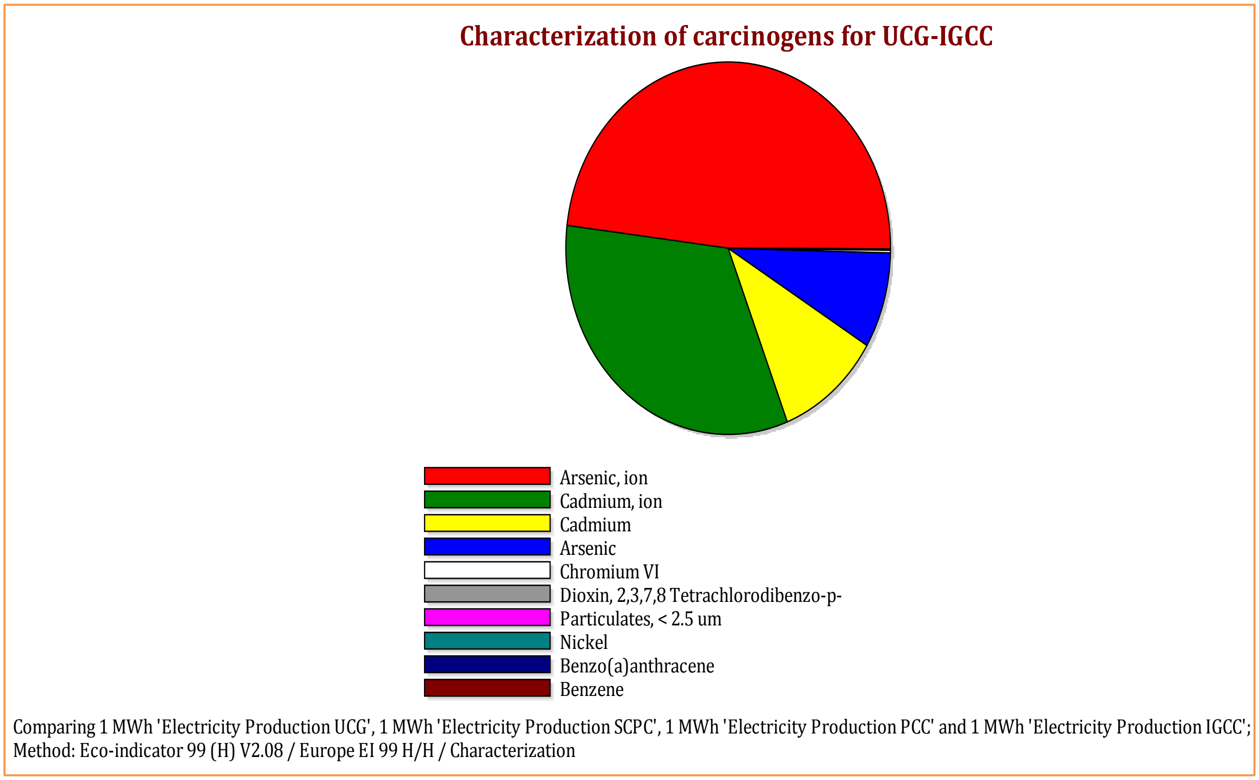


Figure 8.17: Environment impact assessment based on Eco-indicator method



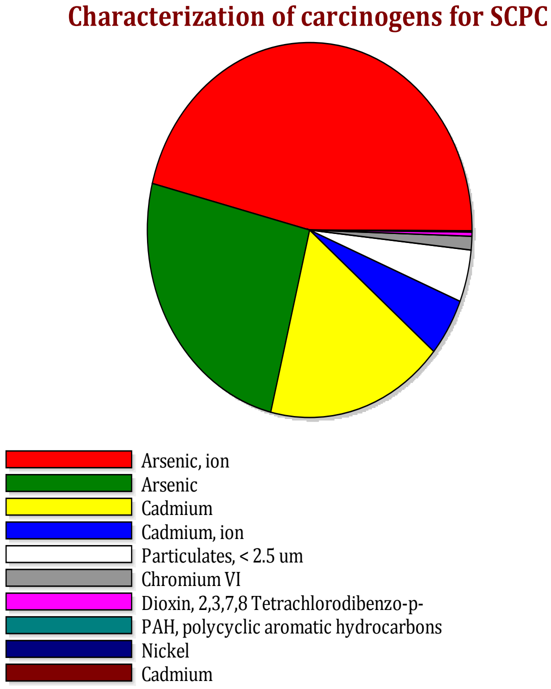
Comparing 1 MWh 'Electricity Production UCG', 1 MWh 'Electricity Production SCPC', 1 MWh 'Electricity Production PCC' and 1 MWh 'Electricity Production IGCC';
Method: Eco-indicator 99 (H) V2.08 / Europe EI 99 H/H / Characterization

Figure 8.18: Characterization of carcinogens for Coal-IGCC



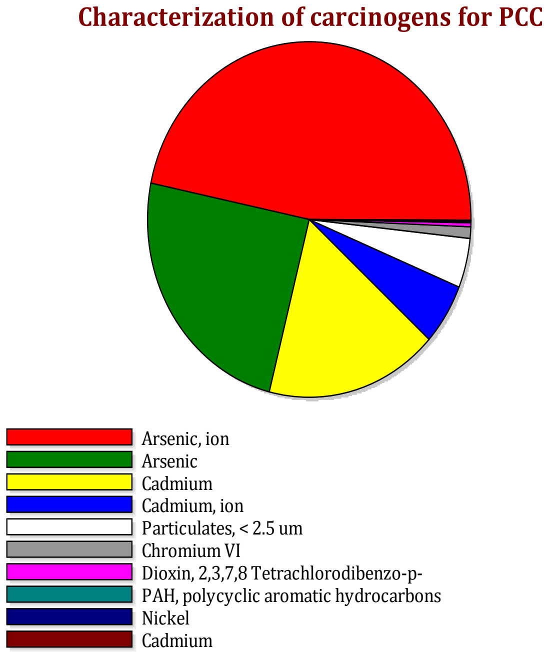
Comparing 1 MWh 'Electricity Production UCG', 1 MWh 'Electricity Production SCPC', 1 MWh 'Electricity Production PCC' and 1 MWh 'Electricity Production IGCC';
Method: Eco-indicator 99 (H) V2.08 / Europe EI 99 H/H / Characterization

Figure 8.19: Characterization of carcinogens for UCG-IGCC



Comparing 1 MWh 'Electricity Production UCG', 1 MWh 'Electricity Production SCPC', 1 MWh 'Electricity Production PCC' and 1 MWh 'Electricity Production IGCC'; Method: Eco-indicator 99 (H) V2.08 / Europe EI 99 H/H / Characterization

Figure 8.20: Characterization of carcinogens for SCPC



Comparing 1 MWh 'Electricity Production UCG', 1 MWh 'Electricity Production SCPC', 1 MWh 'Electricity Production PCC' and 1 MWh 'Electricity Production IGCC'; Method: Eco-indicator 99 (H) V2.08 / Europe EI 99 H/H / Characterization

Figure 8.21: Characterization of carcinogens for PCC

8.16 Chapter Conclusions

Because of some uncertainties in data, variability in the sources of data and the fact that data availability is currently limited for commercial applications of UCG, it is difficult to derive hard conclusions especially when the differences for the life cycles are relatively small. However, this analysis provides a clear picture of the impacts of various technologies and helps in highlighting the areas for improvement of process or processes. This analysis also highlights the fact that improvements in the technologies to reduce the life cycle emissions from coal generation and utilization are fetching good results. The reductions in GHG emissions are about 30% to 40% lesser from the latest plants (both IGCC and Ultra Supercritical pulverized combustion) than conventional PCC plants. UCG is competitive with the latest technologies and has distinct environmental advantages. This analysis shows that UCG has a distinctive place when comparing the technologies for coal resources development based on environmental performance. This technology results in the reduction of greenhouse emissions load of coal's life cycle and provides opportunities for development of coal resources in an environmentally friendly and sustainable manner.

Chapter 9 - Research Conclusions and Future Work

9.1 Research Conclusions

Underground coal gasification has the potential to harness energy from low grade, deep seated, steeply inclined and thin coal seams in an economic, environmentally friendly and sustainable manner. This technology can be applied to abandoned coal mines, remnants of exploited reserves and deposits considered uneconomic and technically difficult for conventional mining methods. Commercial utilization of this technology can help in increasing the recoverable coal reserves and reducing the environmental impacts of mining coal. This technology, in addition to other advanced technologies, can promote the future of clean coal and help in sustaining the coal mining industry.

In this study, the operational parameters of UCG technology were analyzed to determine their significance and to evaluate the effective range of values for proper control of the process. The study indicates that cavity pressures, gas and water flow rates, development of linkage between wells, and continuous monitoring are the most important operating parameters. The availability of sophisticated equipment, the latest machinery and advancements in drilling technology have helped in overcoming the problems of linkage development between process wells, drilling in-seam horizontal wells of required size and configuration, and control of flow rates and gas pressures. State-of the-art monitoring equipment, very accurate and reliable software and dependable online systems have made it possible to extensively monitor, even remotely, the cavity growth, gas flows and pressures, gas quality, and environmental parameters such as water quality, inflow and outflow of contaminants.

The selection of suitable sites for UCG projects was also researched in this study. Past experiments and pilot studies suggest that proper site selection is one of the most important factors in the failure or success of UCG projects. Therefore, site selection criteria are developed in this research based on successes and failures of previous experiments and pilots. The criteria take into account the site characteristics, coal quality parameters, hydrology of the area, availability of infrastructure and regulatory and environmental restrictions on sites. These criteria highlight the merits and demerits of the selected parameters, their importance in site selection and their economic and environmental potentials.

Based on the site selection criteria developed in this research, a GIS model was developed to assist in selecting suitable sites for gasification in any given area of interest. The GIS model is a very helpful tool for selecting suitable sites. This GIS model can be used as a decision support tool as well since it helps in establishing the tradeoff levels between factors, ranking and scaling of factors, and, most importantly, evaluating inherent risks associated with each decision set. The complete procedure for use and development of this model is explained in detail so that anyone interested in the application of this model will find no difficulty in understanding the various steps involved.

The potential of UCG to conform to different frameworks defined to assess the capability and potential of any project that merits the label, "sustainable," has been evaluated in this research. It has been established that UCG can integrate economic activity with ecosystem integrity, respect for the rights of future generations to the use of resources and the attainment of sustainable and equitable social and economic benefits. The important aspects of UCG that need to be considered for its sustainable development are highlighted.

The environmental benefits of UCG have been evaluated in terms of its potential for reduction in greenhouse gas (GHG) emissions. The findings indicate that UCG significantly reduces GHG emissions compared to other competitive coal exploiting technologies. In this research, a model to compute the life cycle greenhouse emissions of UCG has been developed, and it reveals that UCG has distinctive advantages in terms of GHG emissions over other technologies and competes favorably with the latest power generation technologies. In addition to GHG emissions, the environmental impacts of these technologies based on various impact assessment indicators are assessed to determine the position of UCG in the technology mix. It is clear from the analysis that UCG has prominent environmental advantages and has the potential to develop and utilize coal resources in an environmentally friendly and economically sound manner. However, a dedicated effort requiring both government and the private sector to promote further research and development for this technology is needed to establish its commercial potential, especially in the U.S.

9.2 Future Research

Several aspects of UCG need research before its commercialization; however, during the course of this research, two areas for further exploration came into focus: the synergy of UCG and Coalbed Methane (CBM) modules and the application of UCG to gasify multiple seams using the same wells.

CBM is extracted through a network of wells that can be used for gasification of coal seams especially after the wells have been abandoned. The coal seam in the area of CBM wells is generally highly fractured because of the application of hydrofracturing for enhancing methane drainage. This enhanced fracturing can help in creating linkage between process wells. However, the problem of gas flow and contaminant dissemination requires further study. In addition, the control of cavity pressures, cavity development and the inflow of water can be challenging. The consideration of existing infrastructure of wells, however, can reduce capital costs greatly and lead to a more competitive cost of product gas. This will require extensive research to assess strata conditions, coal properties and stress regimes in the area, and extensive field experimentation and pilot scale studies to determine the economic and operational viability of this proposal are needed. The GIS model developed in this research will be a helpful tool when selecting sites considering the existing well structures.

Further research is also required to gasify multiple coalbed seams in the same area using the same well infrastructure. In this case, the flow of gas and well infrastructure needs to be controlled in such a way that injected gases reach all the target seams and product gases are collected at the production wells from each seam. However, field experimentation and pilot scale studies are needed. The schematic of the concept is shown in the Figure 9.1 below.

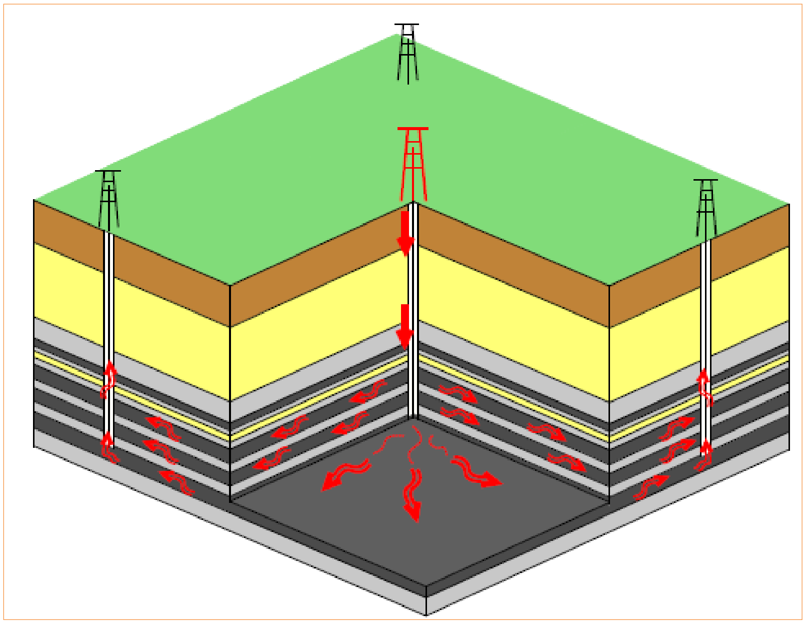


Figure 9.1: UCG application on multiple seams

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Appendices

Appendix A: Energy Requirements for Underground Coal Mine

Table A shows the equipment and energy requirement for a hypothetical U.S. underground coal mine with a production rate of 3322 ton/day based on EERE data [EERE 2002].

Table A: Energy Requirements for Underground Coal Mining

Equipment		Daily utilization	Energy Consumption			
			Single Unit	All Units	All Units	All Units
Type	number of units	hours/unit	(Btu/ton)	(Btu/ton)	(Btu/hour)	(Btu/day)
Electrical Equipment						
Main Fans	11	18	11,900	130,900	24,158,322	434,849,800
LHD	25	18	2,340	58,500	10,796,500	194,337,000
Drills	13	18	317	4,121	760,553	13,689,962
Two Booms Jumbo	20	18	1,740	34,800	6,422,533	115,605,600
Continuous Mining Machine	2	18	8,740	17,480	3,226,031	58,068,560
Raise Borer	1	18	4,690	4,690	865,566	15,580,180
Diamond Drill	1	0.36	6	6	55,367	19,932
Crusher	1	18	1,760	1,760	324,818	5,846,720
Conveyor	1	18	2,370	2,370	437,397	7,873,140
Water Pumps	2	18	72	144	26,576	478,368
Diesel Equipment						
Roof Bolter	1	18	1280	1,280	236,231	4,252,160
Service Trucks	31	18	1840	57,040	10,527,049	189,486,880
ANFO Loaders	6	18	1840	11,040	2,037,493	36,674,880
Total				324,131	59,874,436	1,076,763,182

Appendix B: Energy Requirements for Surface Coal Mine

Table B shows the equipment and energy requirement for a hypothetical U.S. surface coal mine with a production rate of 27,778ton/day based on EERE data [EERE 2002].

Table B: Energy Requirements for Surface Coal Mine

Equipment		Daily utilization	Energy Consumption			
			Single Unit	All Units	All Units	All Units
Type	(number of units)	hours/unit	(Btu/ton)	(Btu/ton)	(Btu/hour)	(Btu/day)
Diesel Equipment						
Rear Dump Trucks	11	20	2,370	26,070	36,208,623	724,172,460
Bull Dozers	7	20	1,680	11,760	16,333,464	326,669,280
Pickup Trucks	20	20	149	2,980	4,138,922	82,778,440
Water Tankers	1	20	1,080	1,080	1,500,012	30,000,240
Pumps	2	20	332	664	922,230	18,444,592
Service Trucks	2	20	293	586	813,895	16,277,908
Bulk Trucks	2	20	293	586	813,895	16,277,908
Graders	1	1	52	52	1,203,713	1,444,456
Electrical Equipment						
Cable Shovels	4	20	2,490	9,960	13,833,444	276,668,880
Rotary Drills	2	20	813	1,626	2,258,351	45,167,028
Total				55,364	78,026,550	1,537,901,192

Appendix C: Energy and Material Requirements for UCG

Table C shows the energy and materials inflow for electricity production using underground coal gasification.

Table C: Energy and Material Requirements for UCG

Data for UCG	
Calorific value of coal	26.4 MJ/kg
Calorific value of Gas	5.0 MJ/m^3
Turbine efficiency	50%
Plant Capacity	300 MW
Operating capacity factor	80%
Coal resource recovery	75%
Total plant life	20 years
Coal requirement	1, 650,000 ton /year
Gas requirements	3,784,320,000 m^3/year
Water	2.33×10^6 m^3/year
Copper ore (for wiring, generators)	234 ton/year
Oil	4,467.60 GJ/year
UCG electrical consumption	8.47 MW

Appendix D: Energy Requirements for Coal Preparation Plant

Table D shows the equipment and energy requirement for coal preparation plant with a feed rate of 3,332 ton per day or 185 tons per hour, based on EERE data [EERE 2002].

Table D: Energy Requirements for Surface Coal Mine

Equipment		Daily utilization	Energy Consumption			
			Single Unit	All Units	All Units	All Units
Type	(number of units)	hours/unit	(Btu/ton)	(Btu/ton)	(Btu/hour)	(Btu/day)
Grinding Mill	1	18	93,200	93,200	17,200,578	309,610,400
Centrifuge	1	18	585	585	107,965	1,943,370
Flotation Machine	1	18	359	359	66,255	1,192,598
Screens	1	18	238	238	43,924	790,636
Magnetic Separator	1	18	121	121	22,331	401,962
Total				94,503	17,441,054	313,938,966

Appendix E: Life Cycle Components: Coal Production

The model in Figure A shows the coal production component of life cycle greenhouse emissions for electricity generation from coal plants. The GHG emissions are calculated as $kgCO_2eq$ per ton of mined coal using GWP values estimated by 2007 IPCC for 100-year timeframe. 69% coal is from surface mines and 31% is from underground coal mines, representing the U.S. average. This part is common for PCC, SCPC and Coal-IGCC, as it calculates emission per ton of coal, not for the coal requirements for the plant.

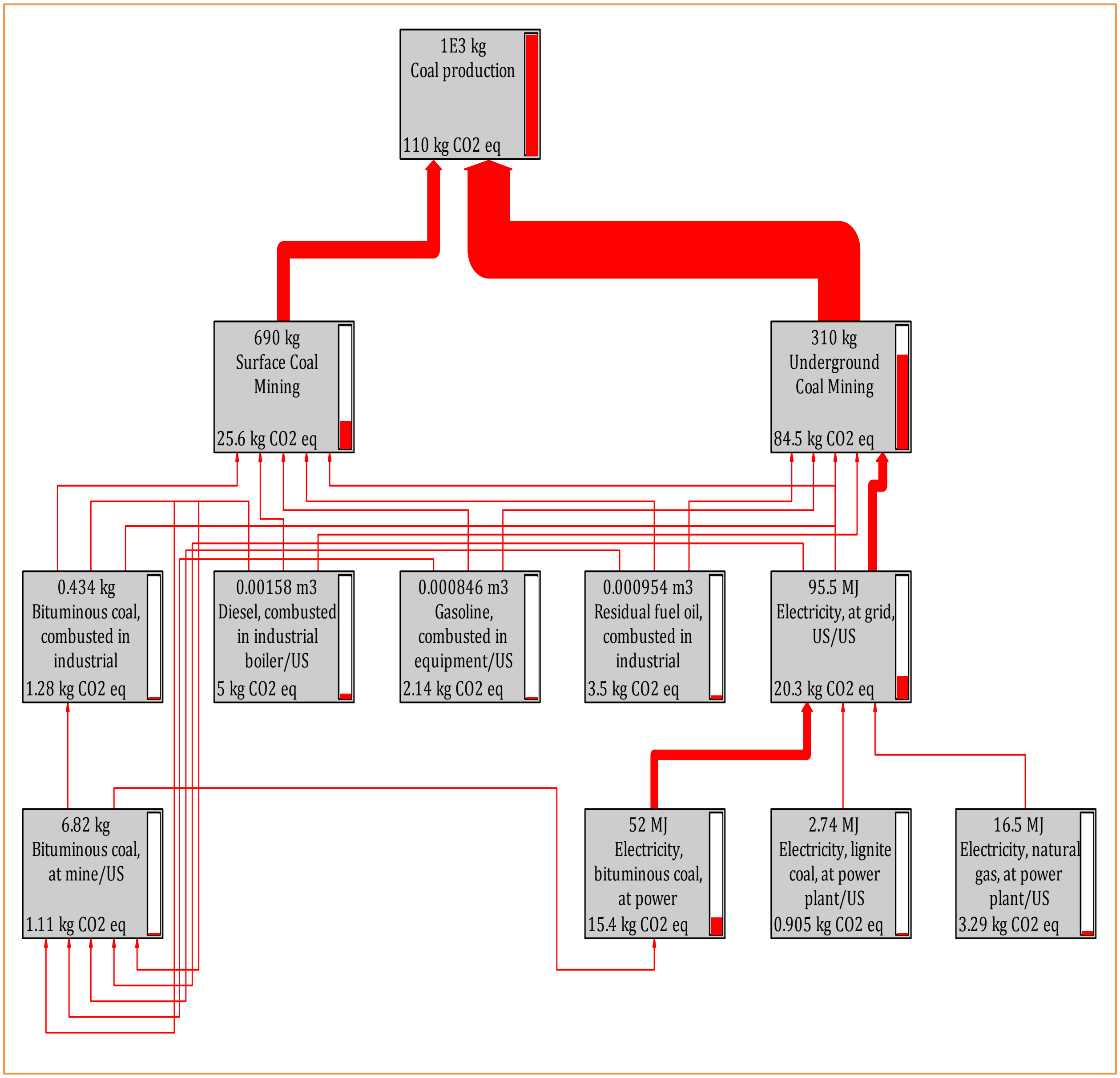


Figure A: GHG contributions by coal production component

Appendix F: Life Cycle Components: Coal Processing

The model in Figure B shows the coal-processing component of life cycle greenhouse emissions for electricity generation from coal plants. The GHG emissions are calculated as kgCO$_2$eq per ton of processed coal using GWP values estimated by 2007 IPCC for 100-year timeframe. This part is common for PCC, SCPC and Coal-IGCC, as it calculates emissions per ton of coal, not for the coal requirements for the plant.

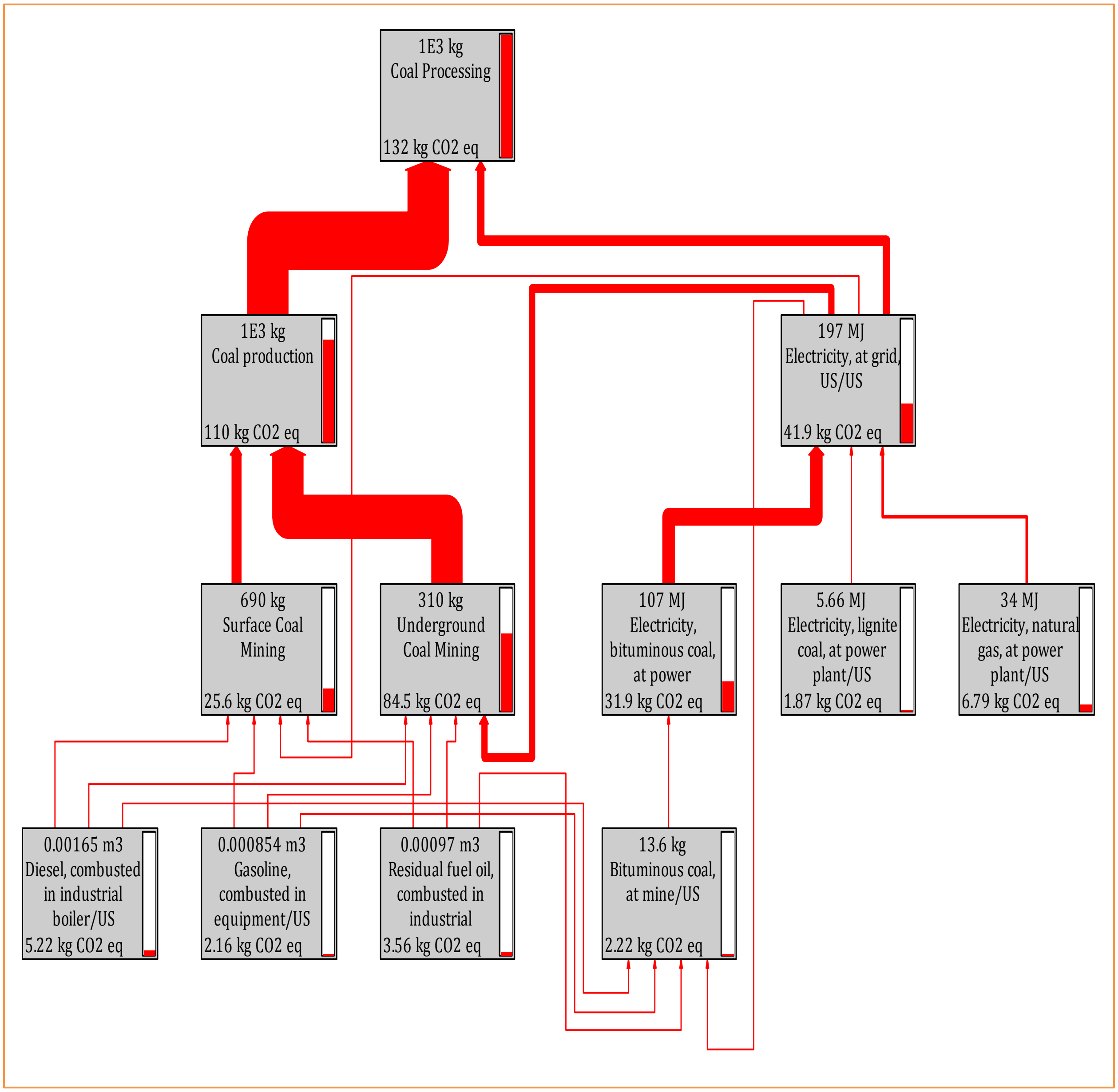


Figure B: GHG contributions by coal processing component

Appendix G: Life Cycle Components: Coal Transport

This model in Figure C shows life cycle greenhouse emissions from coal transport component. The GHG emissions are calculated as kgCO_2eq per ton of transported coal using GWP values estimated by 2007 IPCC for 100-year timeframe. This part is common for PCC, SCPC and Coal-IGCC plants, as it calculates emission per ton of coal, not for the coal requirements for the plant. 75% of coal is transported through trains, 15% through barges and 10% through trucks that represent the U.S. average for coal transportation.

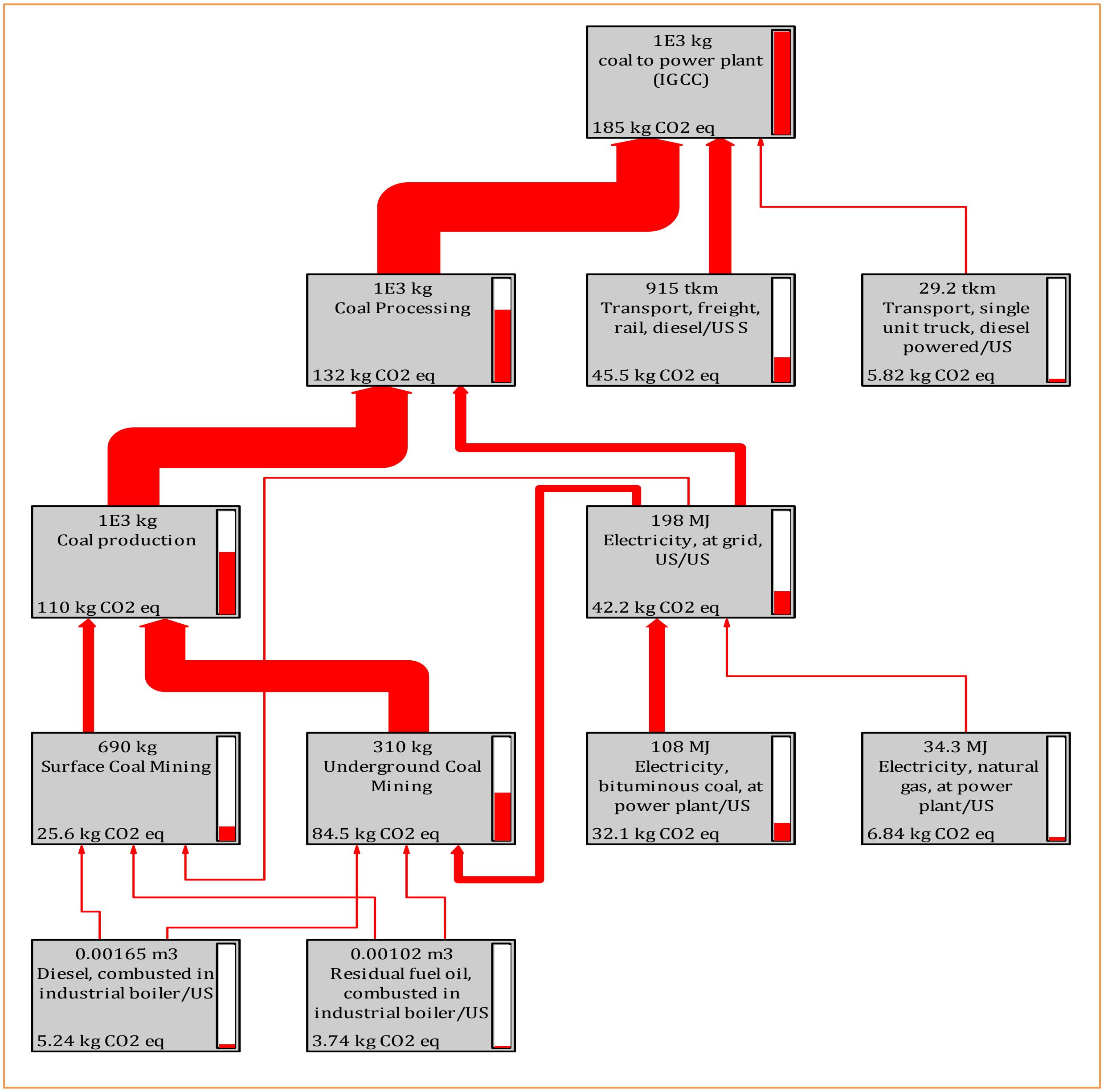


Figure C: GHG contributions by coal production component

Appendix H: Complete PCC Life Cycle Model showing all Nodes and Links

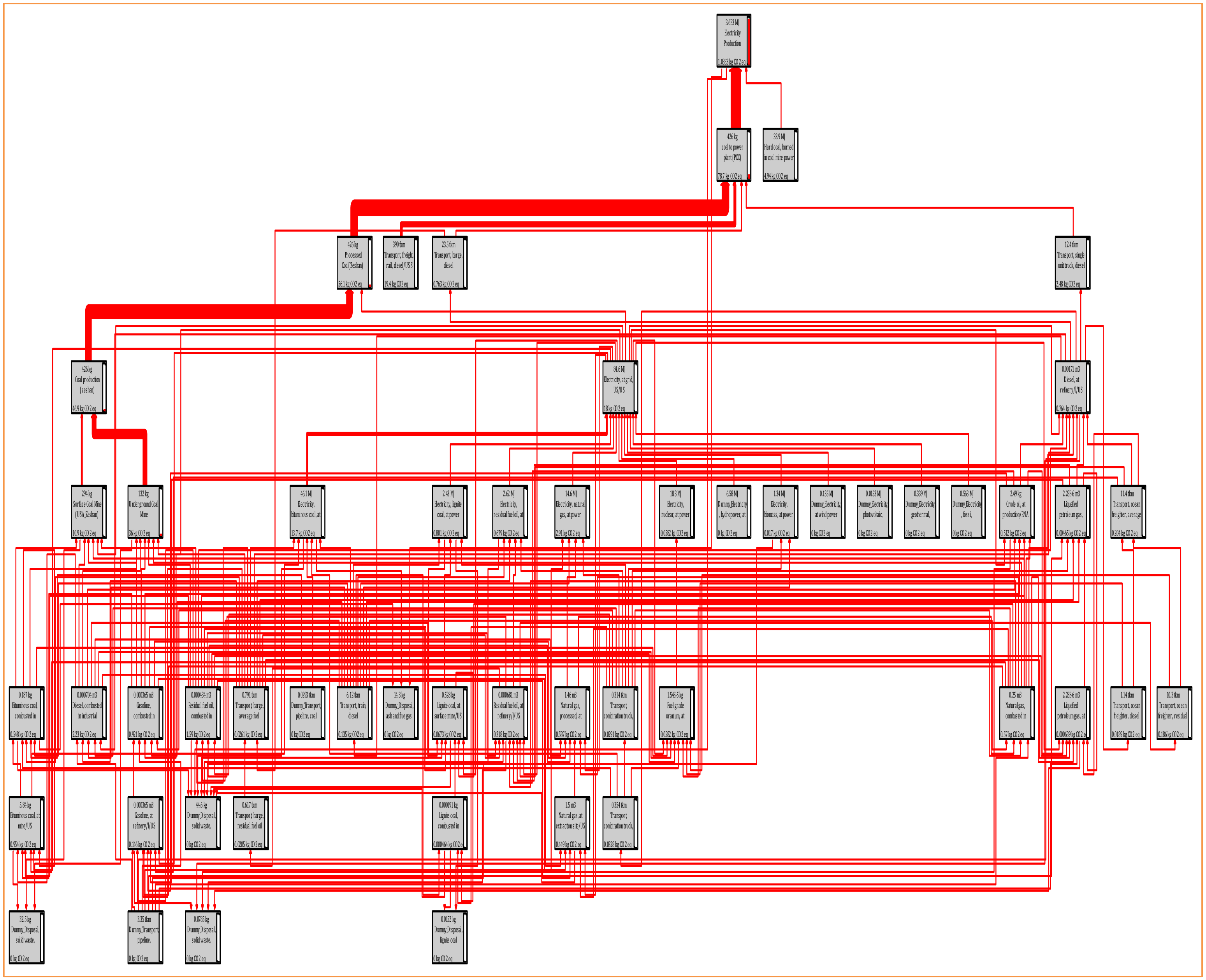


Figure D: Complete PCC life cycle model

Appendix I: Complete SCPC Life Cycle Model showing all Nodes

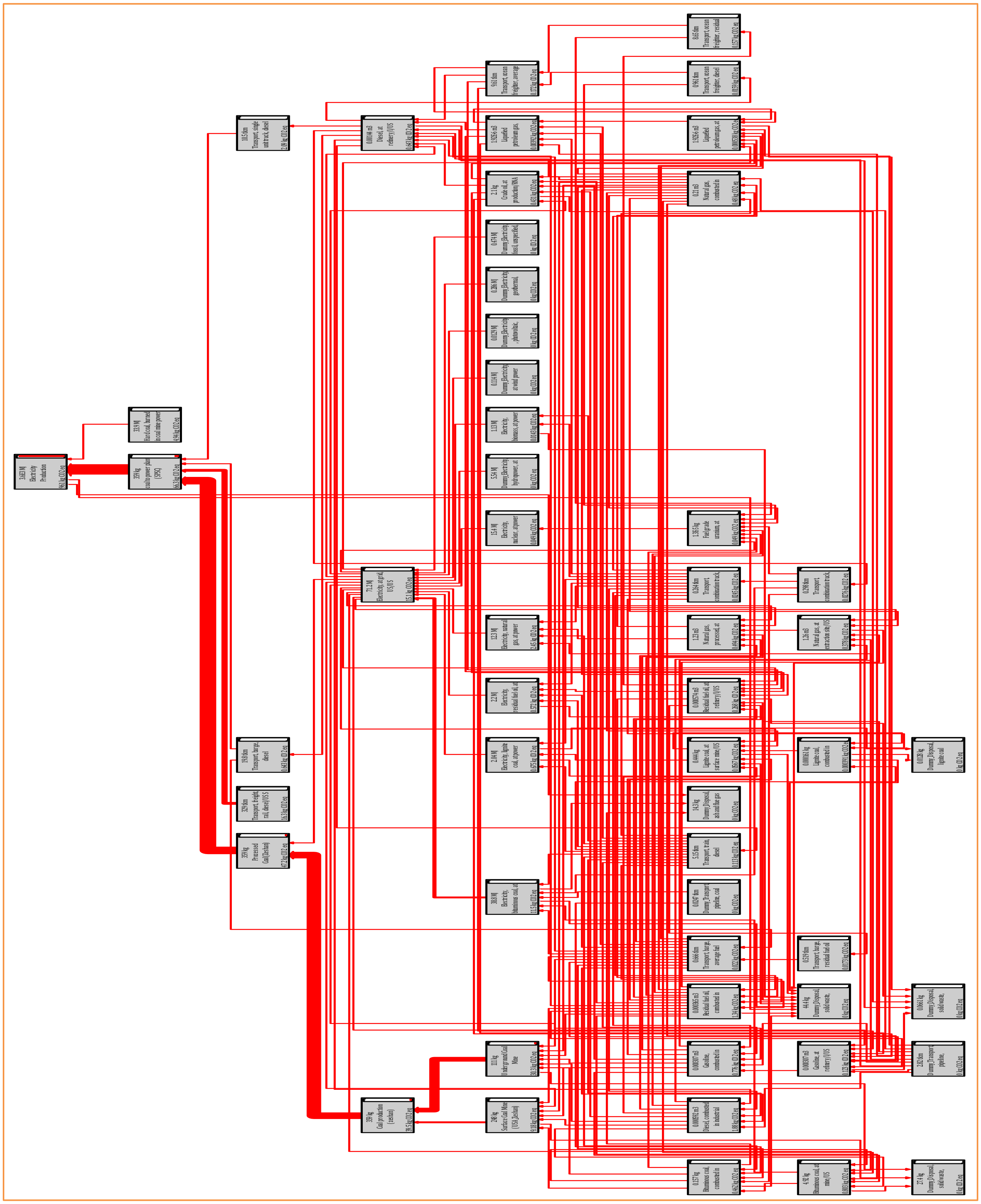


Figure E: Complete SCPC life cycle model

Appendix J: Complete Coal-IGCC Life Cycle Model showing all Nodes

Figure F: Complete IGCC life cycle model

Appendix K: Life Cycle Components: UCG Production

This model in Figure G shows life cycle greenhouse emissions from UCG production component. The GHG emissions are calculated as kgCO$_2$eq per m^3 of syngas using GWP values estimated by 2007 IPCC for 100-year timeframe. All the materials and energy flows, as well as emissions are attributed to 1m^3 syngas production.

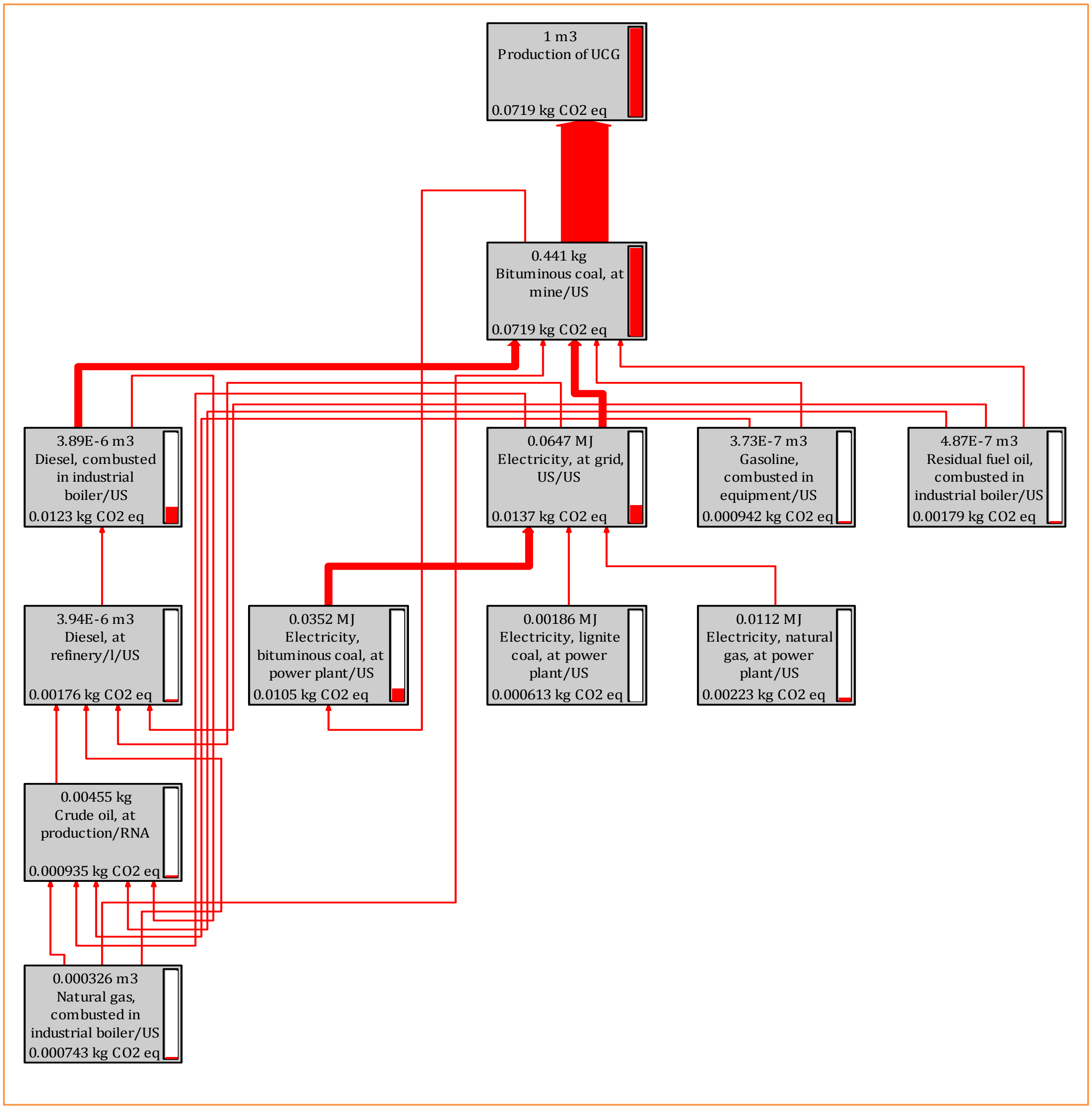


Figure G: GHG contributions by UCG production component

Appendix L: Life Cycle Components: UCG Transport

This model in Figure H shows life cycle greenhouse emissions from UCG transport. The GHG emissions are calculated as $kgCO_2eq$ per m^3 of syngas using GWP values estimated by 2007 IPCC for 100-year timeframe. All the materials and energy flows, as well as emissions are attributed to $1m^3$ syngas transport. The transport network for natural gas has been used in this model for UCG transportation.

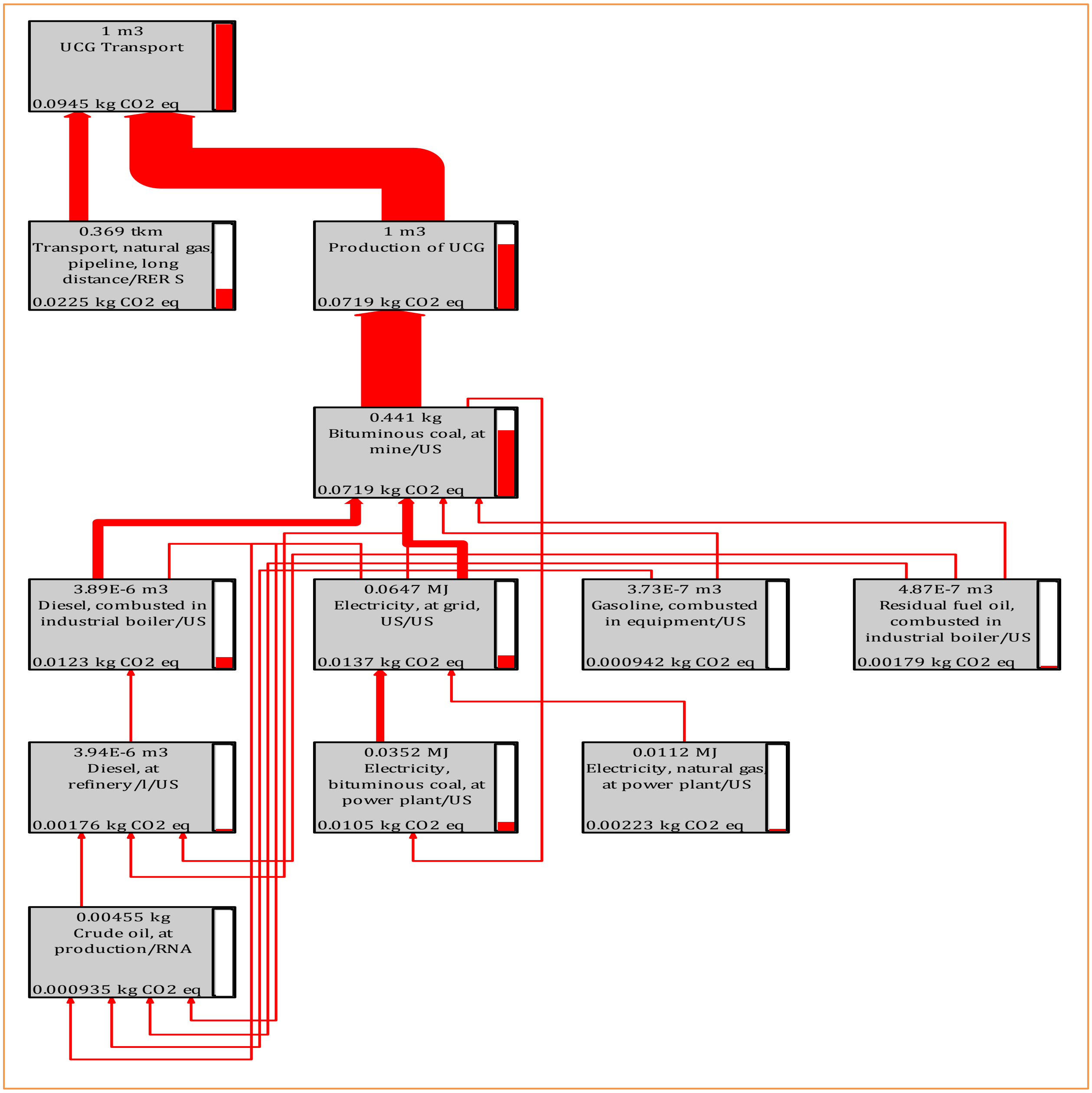


Figure H: GHG contributions by UCG transportation component

Appendix M: Complete UCG Life Cycle

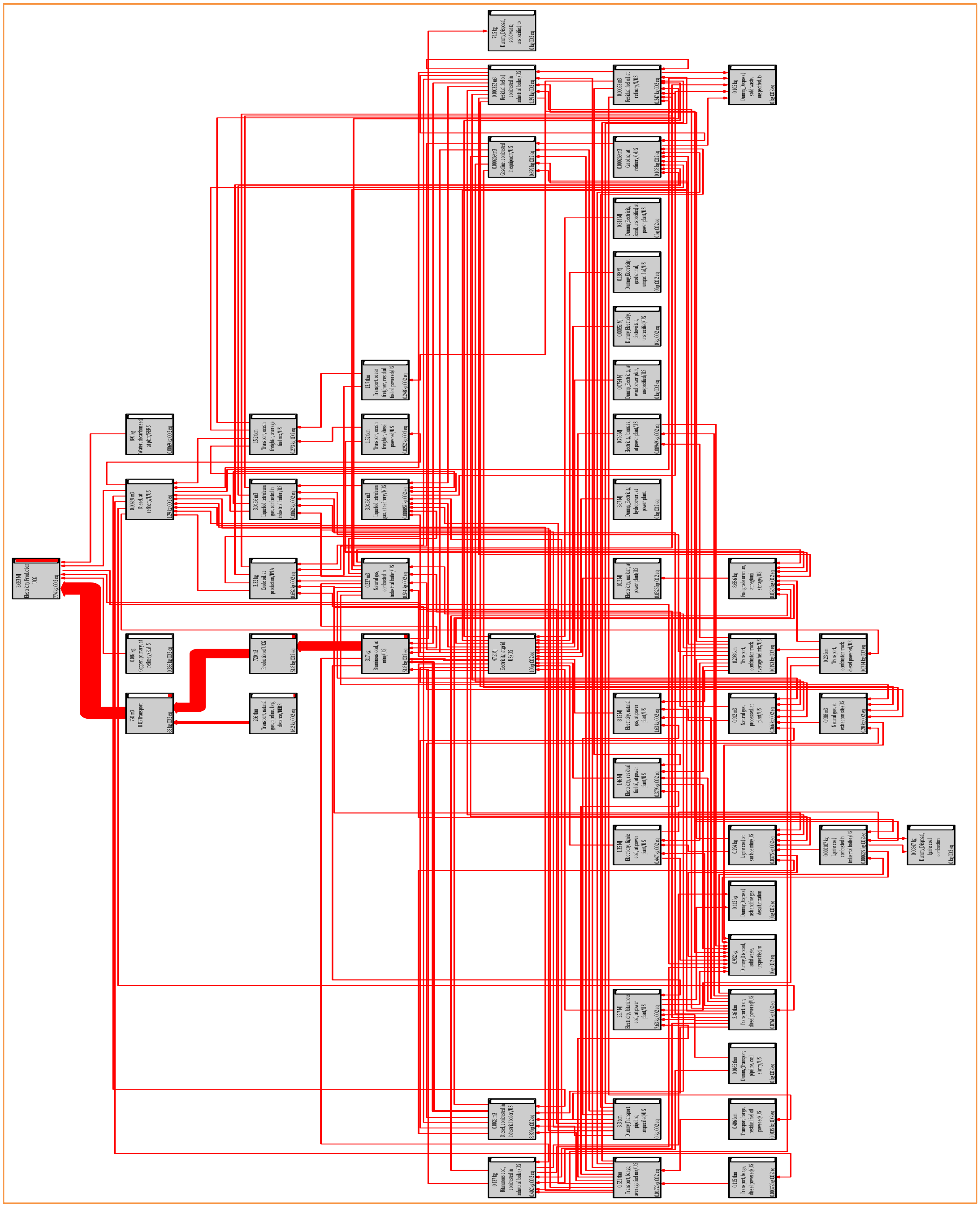


Figure I: Complete UCG life cycle model

Appendix N: Characterization based on Cumulative Energy Demand

Cumulative energy demand is a resource-oriented indicator that represents direct and indirect energy used during the life cycle and includes energy consumptions for the extraction of materials, manufacturing and disposal of materials [Huijbregts, Hellweg et al. 2010]. For calculating cumulative energy demand, the weighting factor of 1 is assigned to each impact category. For characterization, the given energy sources are divided into 5 categories, Nonrenewable fossils, Nonrenewable nuclear, renewable biomass, renewable wind, solar, geothermal and renewable water [PRe Consultants 2010]. Figure J shows the characterization of processes based on this method.

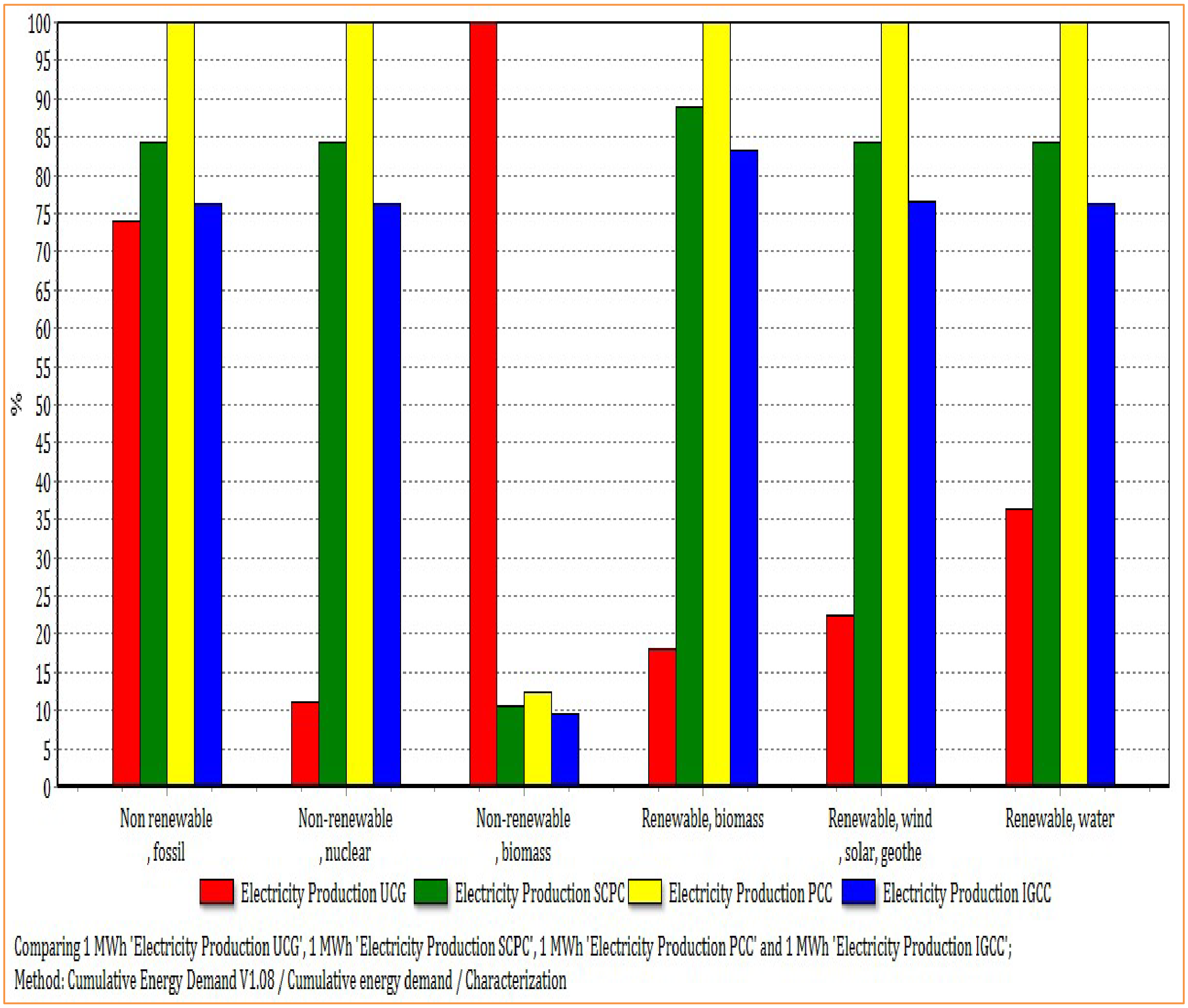
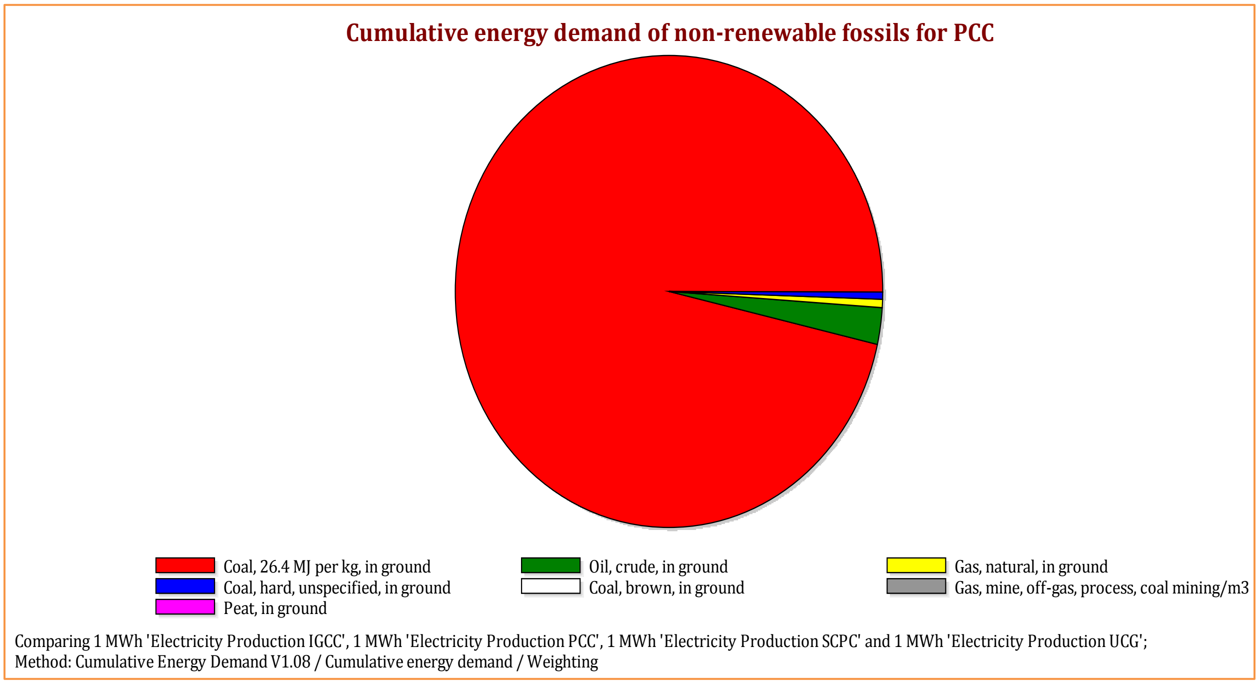


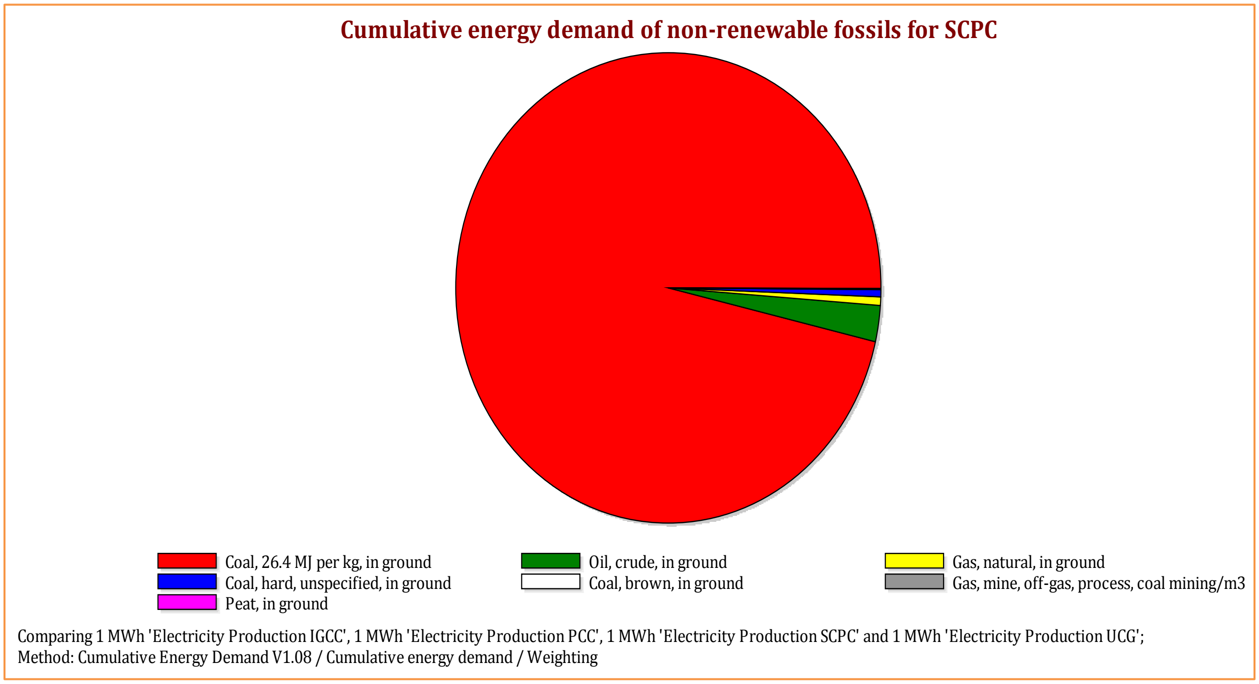
Figure J: Characterization based on cumulative energy demand method

Appendix O: Weighting based on Cumulative Energy Demand

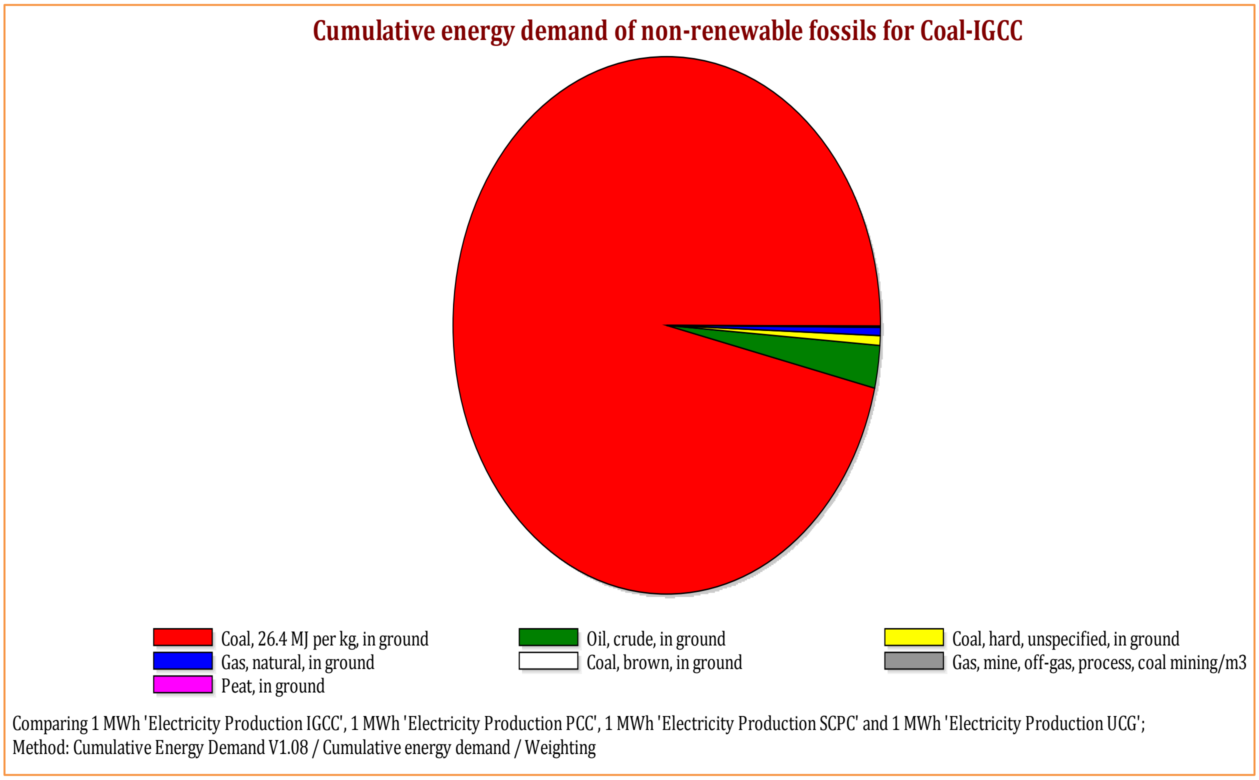
The pie charts show contribution of different sources for cumulative energy demand in the category of non-renewable fossils for these generation technologies. As is clear from these charts, the major substance is coal.


Cumulative energy demand of non-renewable fossils for PCC

Comparing 1 MWh 'Electricity Production IGCC', 1 MWh 'Electricity Production PCC', 1 MWh 'Electricity Production SCPC' and 1 MWh 'Electricity Production UCG';
Method: Cumulative Energy Demand V1.08 / Cumulative energy demand / Weighting

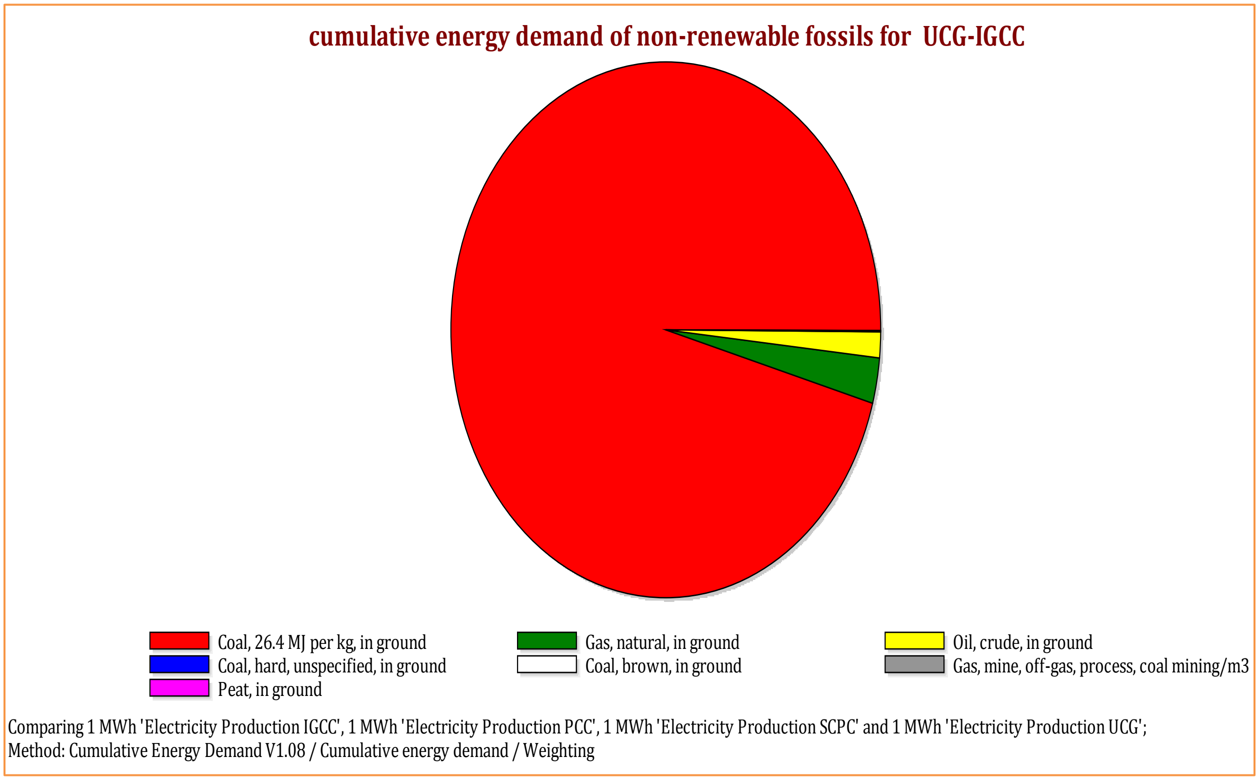

Cumulative energy demand of non-renewable fossils for SCPC

Comparing 1 MWh 'Electricity Production IGCC', 1 MWh 'Electricity Production PCC', 1 MWh 'Electricity Production SCPC' and 1 MWh 'Electricity Production UCG';
Method: Cumulative Energy Demand V1.08 / Cumulative energy demand / Weighting



Cumulative energy demand of non-renewable fossils for Coal-IGCC

Comparing 1 MWh 'Electricity Production IGCC', 1 MWh 'Electricity Production PCC', 1 MWh 'Electricity Production SCPC' and 1 MWh 'Electricity Production UCG';
Method: Cumulative Energy Demand V1.08 / Cumulative energy demand / Weighting

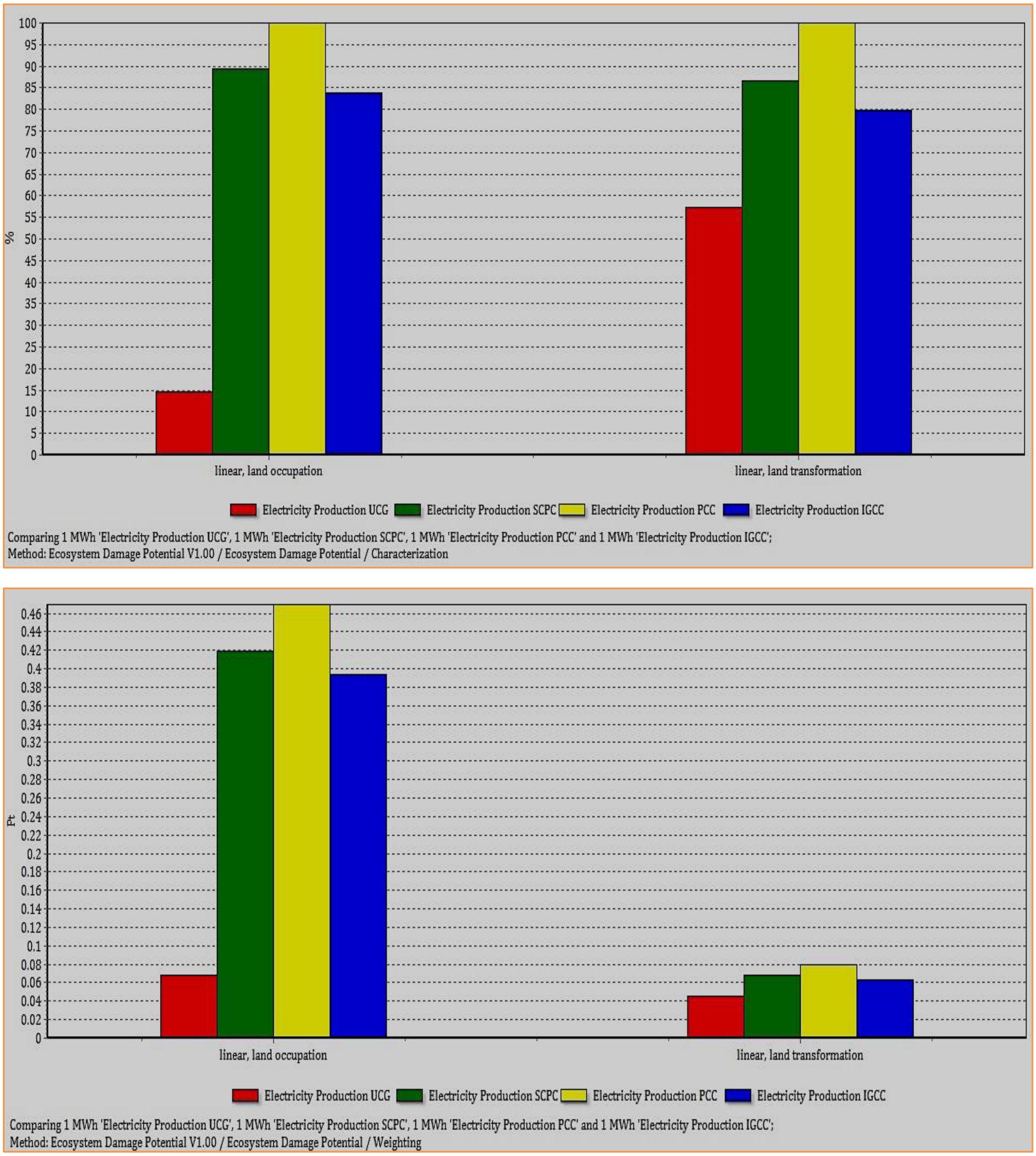


cumulative energy demand of non-renewable fossils for UCG-IGCC

Comparing 1 MWh 'Electricity Production IGCC', 1 MWh 'Electricity Production PCC', 1 MWh 'Electricity Production SCPC' and 1 MWh 'Electricity Production UCG';
Method: Cumulative Energy Demand V1.08 / Cumulative energy demand / Weighting

Appendix P: Characterization based on Ecosystem Damage Potential

This method characterizes the impacts of land use and land transformation on species diversity, shown in Figure K . The weighting factor is 1 for each impacting category.



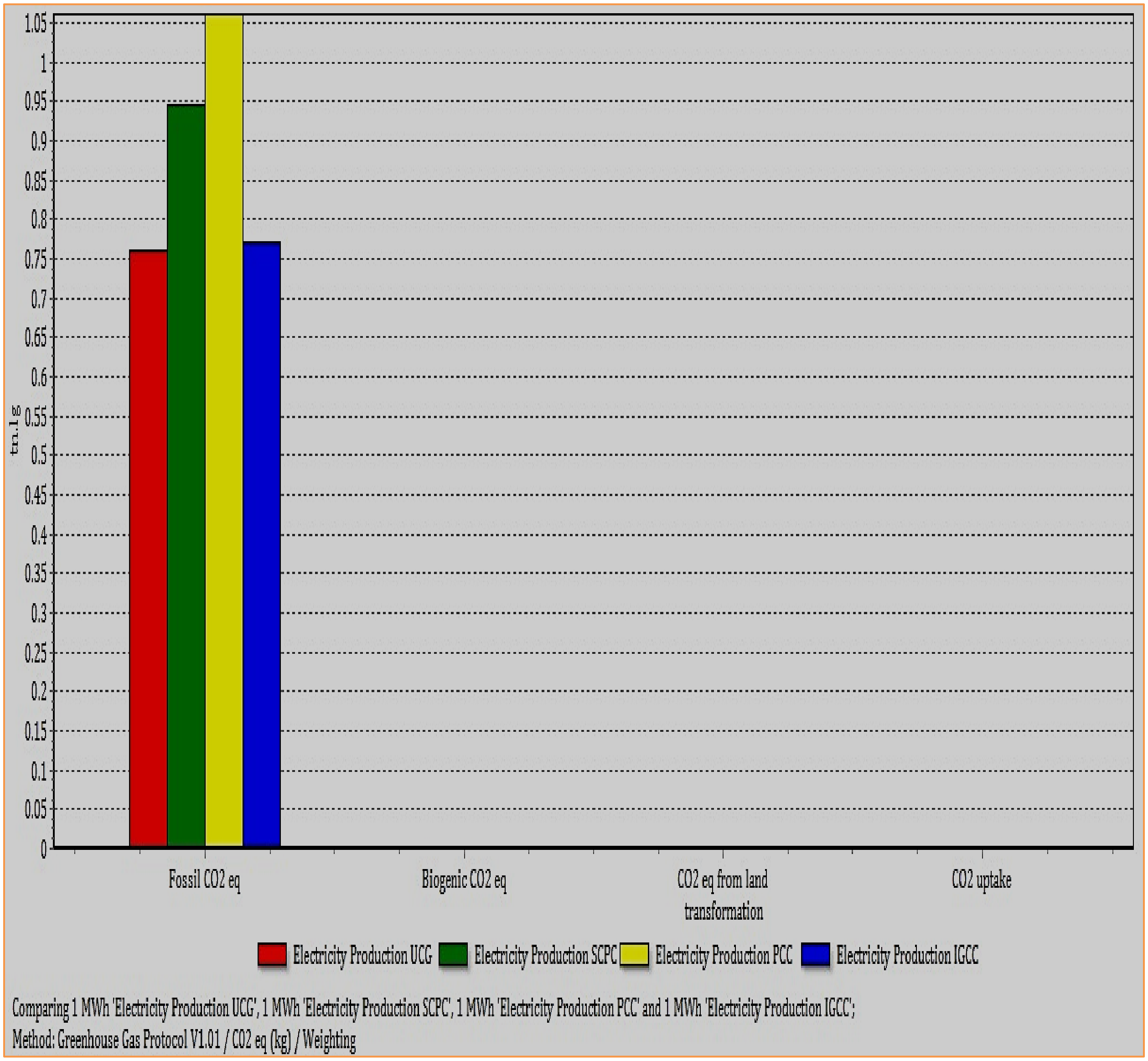
Comparing 1 MWh 'Electricity Production UCG', 1 MWh 'Electricity Production SCPC', 1 MWh 'Electricity Production PCC' and 1 MWh 'Electricity Production IGCC';
Method: Ecosystem Damage Potential V1.00 / Ecosystem Damage Potential / Characterization

Comparing 1 MWh 'Electricity Production UCG', 1 MWh 'Electricity Production SCPC', 1 MWh 'Electricity Production PCC' and 1 MWh 'Electricity Production IGCC';
Method: Ecosystem Damage Potential V1.00 / Ecosystem Damage Potential / Weighting

Figure K: Characterization and weighting based on ecosystem damage potential

Appendix Q: Weighting based on Greenhouse Gas Protocol

This indicator calculates the GHG emissions in CO_2e and categorizes the CO_2 emissions into four types; from fossil sources, biogenic carbon emission, carbon storage and emissions from land transformation [PRe Consultants 2010]. CO_2 from use of fossil fuels is major contributor of total GHG emissions as shown in Figure L .

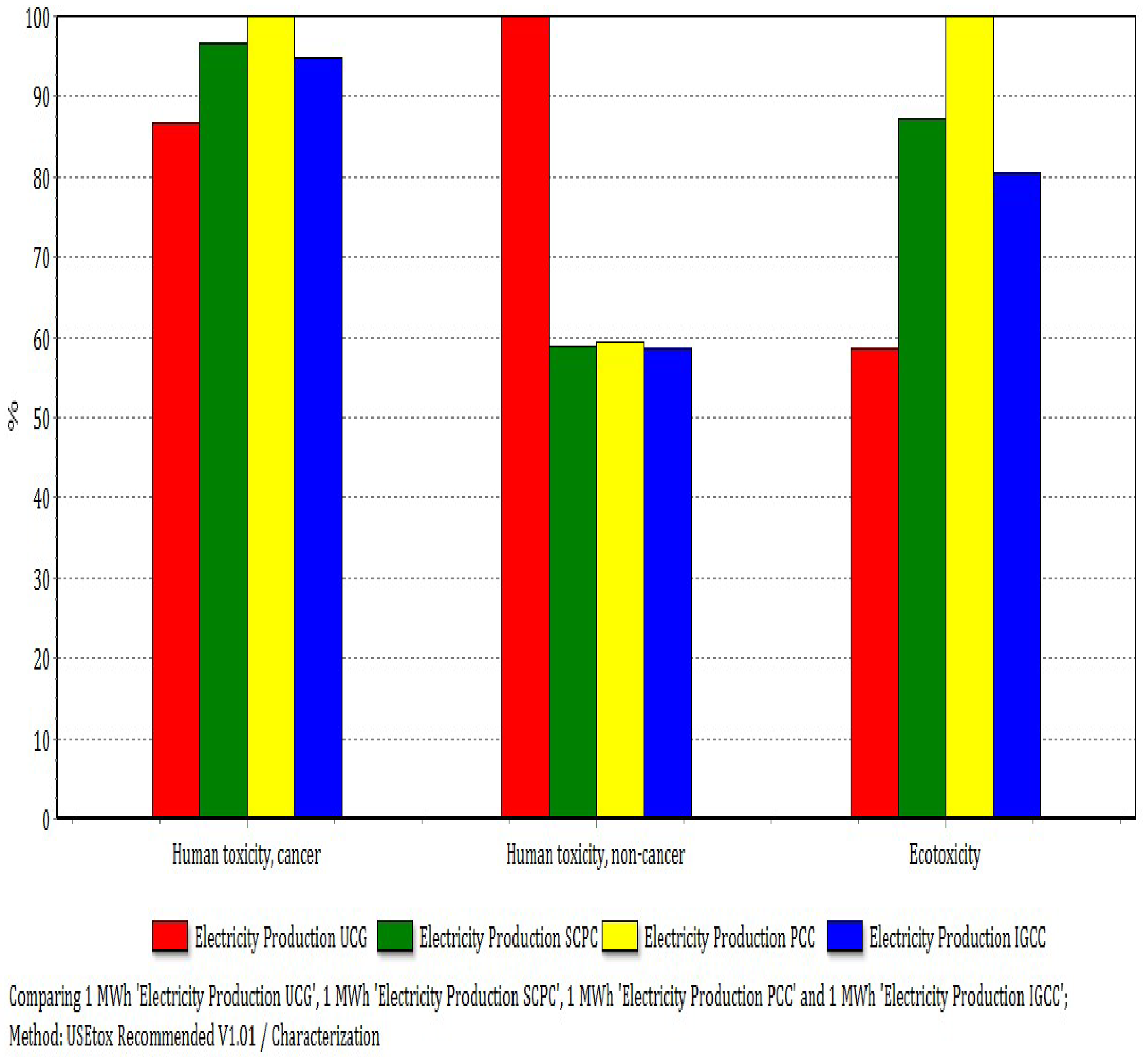


Comparing 1 MWh 'Electricity Production UCG', 1 MWh 'Electricity Production SCPC', 1 MWh 'Electricity Production PCC' and 1 MWh 'Electricity Production IGCC';
Method: Greenhouse Gas Protocol V1.01 / CO2 eq (kg) / Weighting

Figure L: Weighting based on greenhouse gas protocol

Appendix R: Characterization based on USEtox method

The USEtox method characterizes the human and ecotoxicological impacts of life cycle emissions. It characterizes the carcinogenic, non-carcinogenic and total impacts on urban air, rural air, fresh water, agricultural and naturals soils [PRe Consultants 2010]. The measurements for ecotoxicological effect factors are expressed in Potentially Affected Fraction (PAF) of species due to changes in chemical concentrations (PAF.m^3/kg) [Huijbregts, Hauschild et al. 2010]. UCG has lower ecotoxicity score and higher human toxicity impact for non-cancer category, shown by Figure M .



Comparing 1 MWh 'Electricity Production UCG', 1 MWh 'Electricity Production SCPC', 1 MWh 'Electricity Production PCC' and 1 MWh 'Electricity Production IGCC';
Method: USEtox Recommended V1.01 / Characterization

Figure M: Characterization based on USEtox method

Appendix S: Characterization based on North American BEES method

"BEES" stands for Building for Environmental and Economic Sustainability. This software is developed by the National Institute of Standards and Technology (NIST) to calculate life cycle emissions and costs [PRe Consultants 2010]. Figure N shows characterization based on this method.

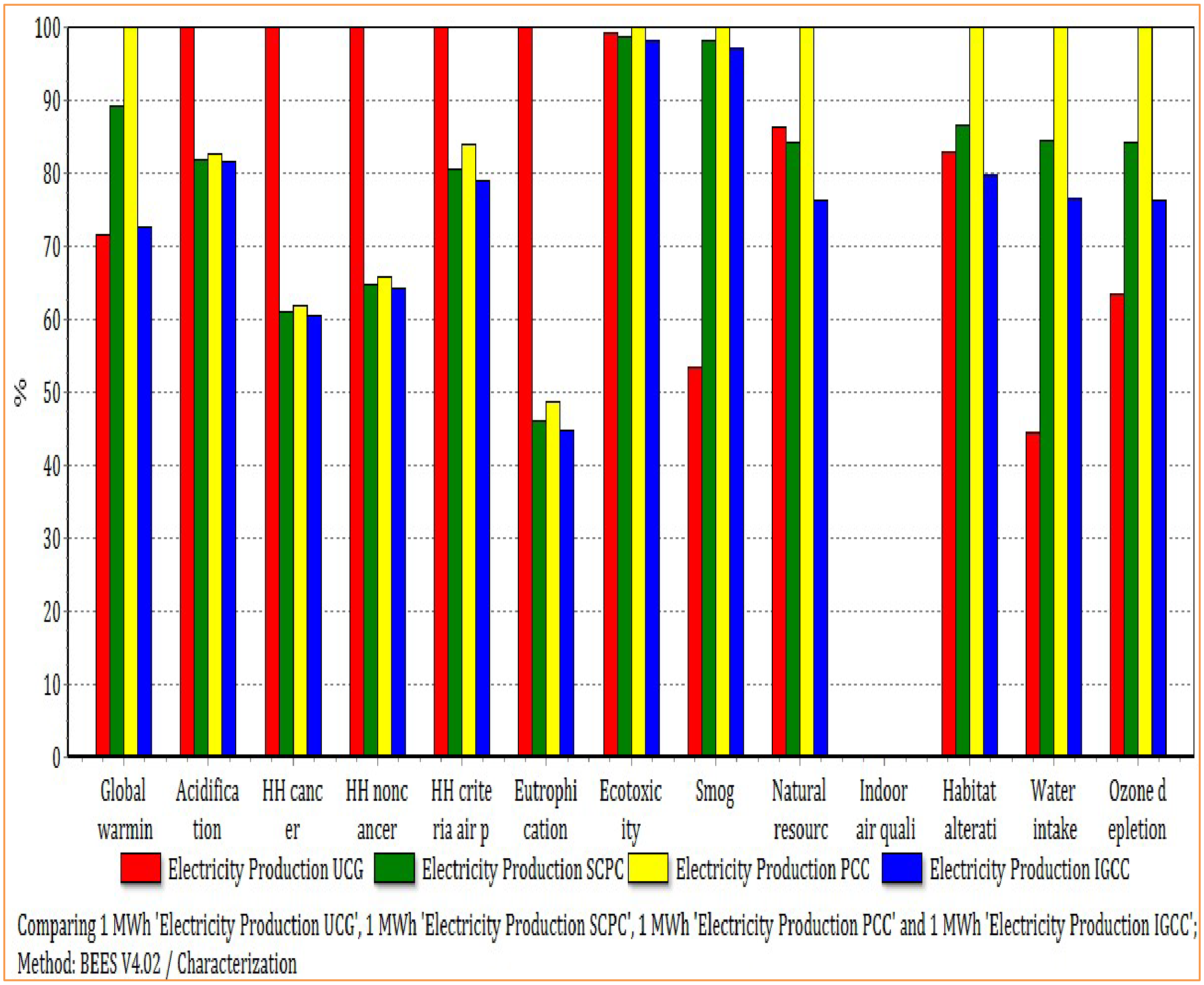


Figure N: Characterization based on BEES method

Appendix T: Characterization based on EPA's TRACI method

TRACI stands for tool for The Reduction and Assessment of Chemical and Other Environmental Impacts, developed by the EPA specifically for the U.S., based on average values for the U.S. locations. The characterization is based on potential environmental impacts including ozone depletion, global warming potential, acidification, eutrophication, smog formation, ecotoxicity, human health, cancer effects, non-cancer effects, fossil fuel depletion, and land-use effects. UCG has higher impacts on ozone depletion, acidification, eutrophication, non-carcinogenic and ecotoxicity and lower impacts for global warming, smog formation, respirator effects and carcinogens, shown by Figure O.

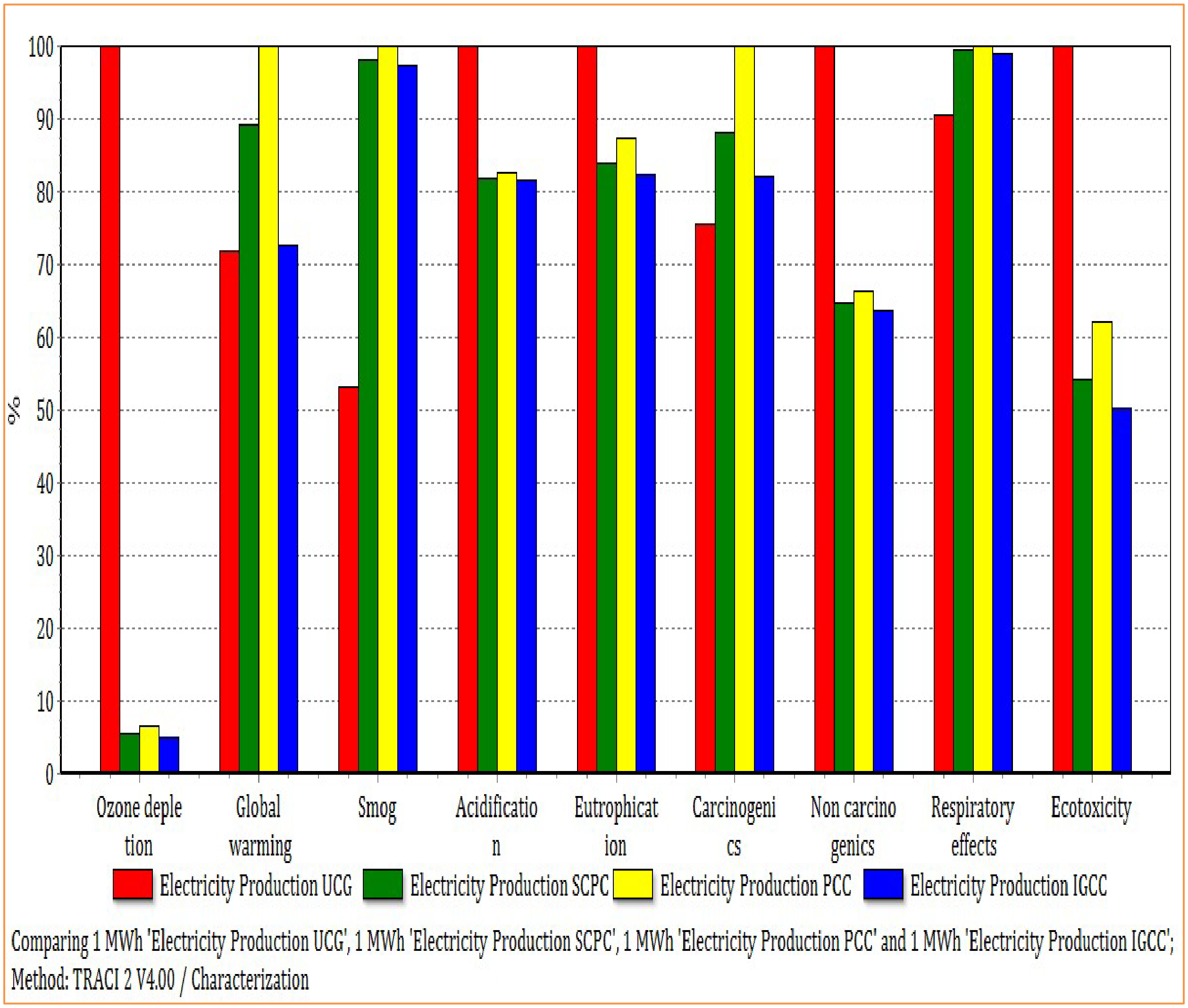
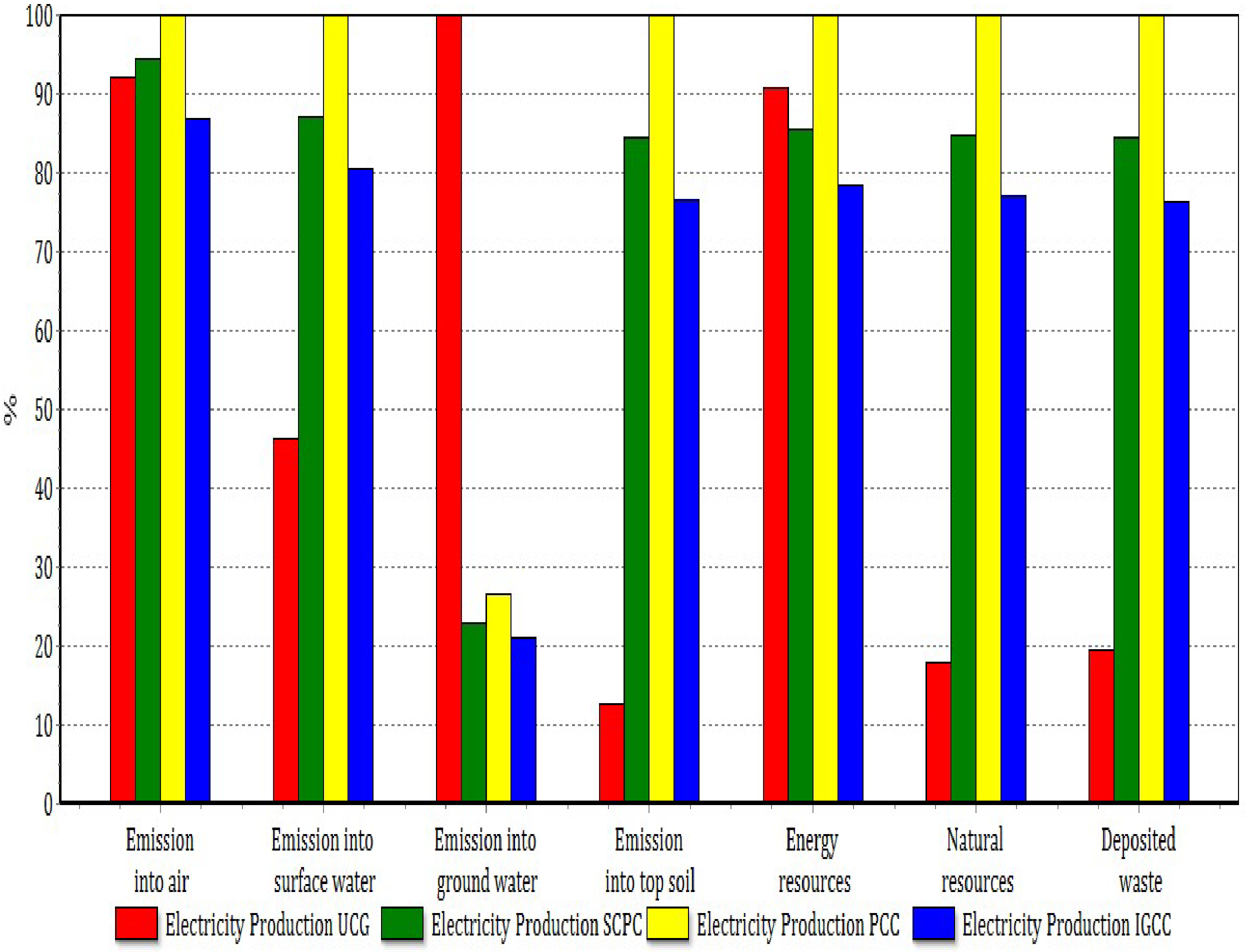


Figure O: Characterization based on TRACI method

Appendix U: Characterization based on Ecological Scarcity 2006

Ecological scarcity is a European method for impact assessment based on distance to target principle [PRe Consultants 2010]. The method has seven impact categories and UCG has lower impacts in all categories except emissions into ground water, as shown in Figure P .

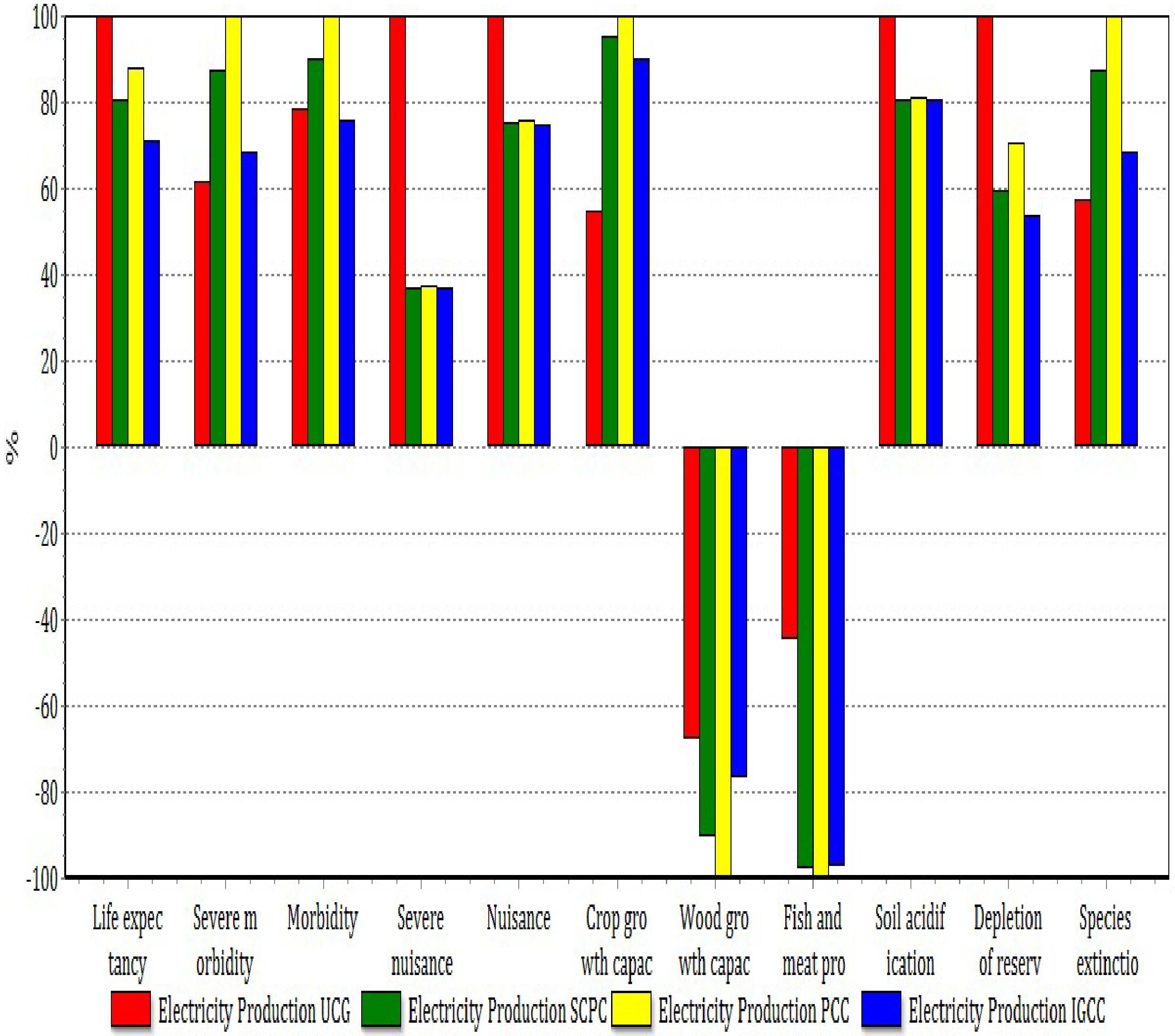


Comparing 1 MWh 'Electricity Production UCG', 1 MWh 'Electricity Production SCPC', 1 MWh 'Electricity Production PCC' and 1 MWh 'Electricity Production IGCC';
Method: Ecological Scarcity 2006 V1.06 / Ecological scarcity 2006 / Characterization

Figure P: Characterization based on ecological scarcity method

Appendix V: Damage Assessment based on EPS 2000

EPS (Environmental Priority Strategies) is a damage-oriented method measuring impacts in terms of willingness to pay to restore changes. The indicator measures in ELU or environment load units. This method takes into account impacts on human health, ecosystem production capacity, abiotic stock resources and biodiversity [PRe Consultants 2010]. The environmental damage assessment based on this method is shown in Figure Q.



Comparing 1 MWh 'Electricity Production UCG', 1 MWh 'Electricity Production SCPC', 1 MWh 'Electricity Production PCC' and 1 MWh 'Electricity Production IGCC'; Method: EPS 2000 V2.06 / EPS / Damage assessment

Figure Q: Environmental damage assessment based on EPS 2000 method

Appendix W: Damage Assessment based on Impact 2002+

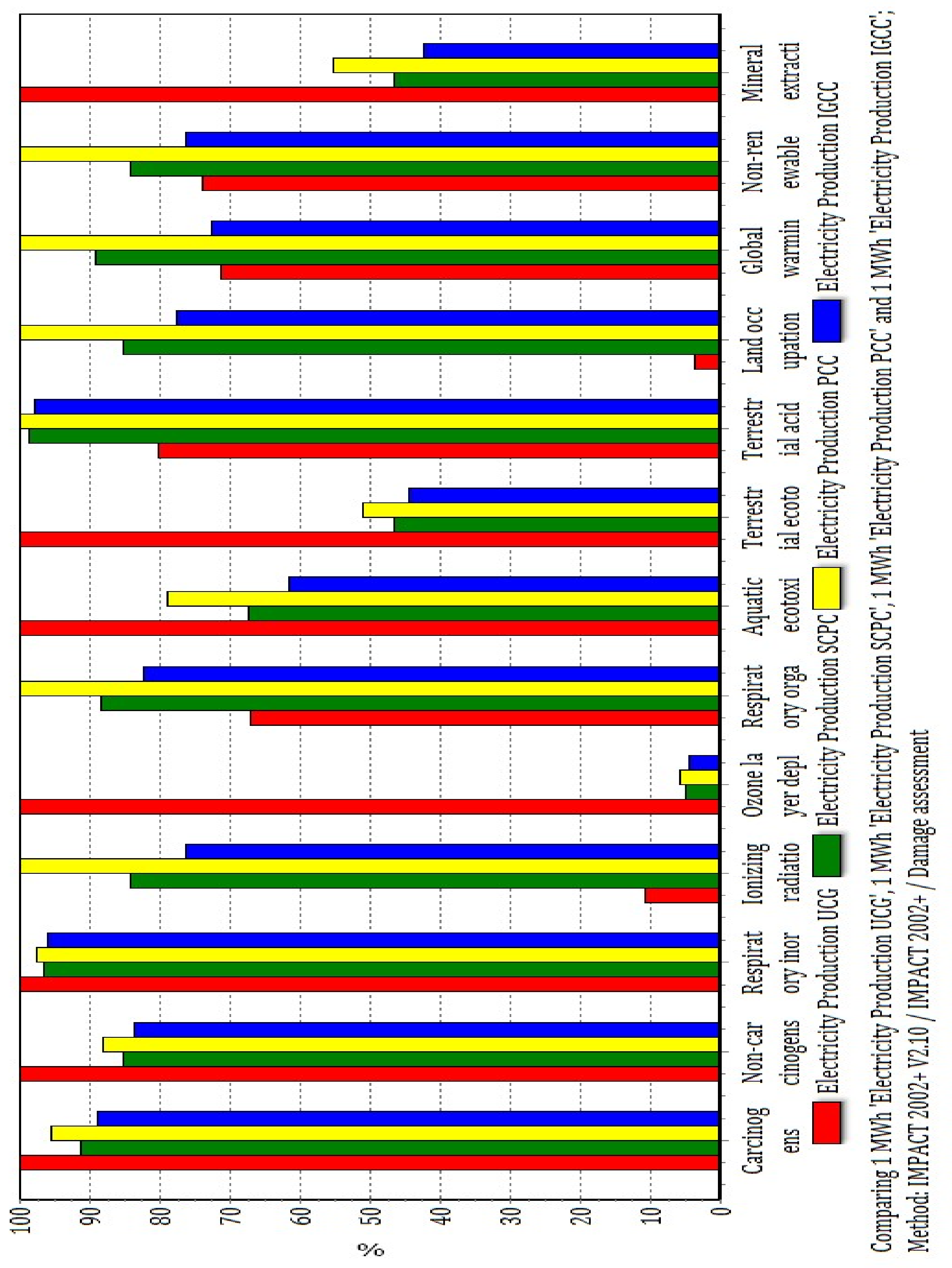


Figure R: Environmental damage assessment based on impact 2002+ method

Appendix X: Damage Assessment based on ReCiPe Endpoint

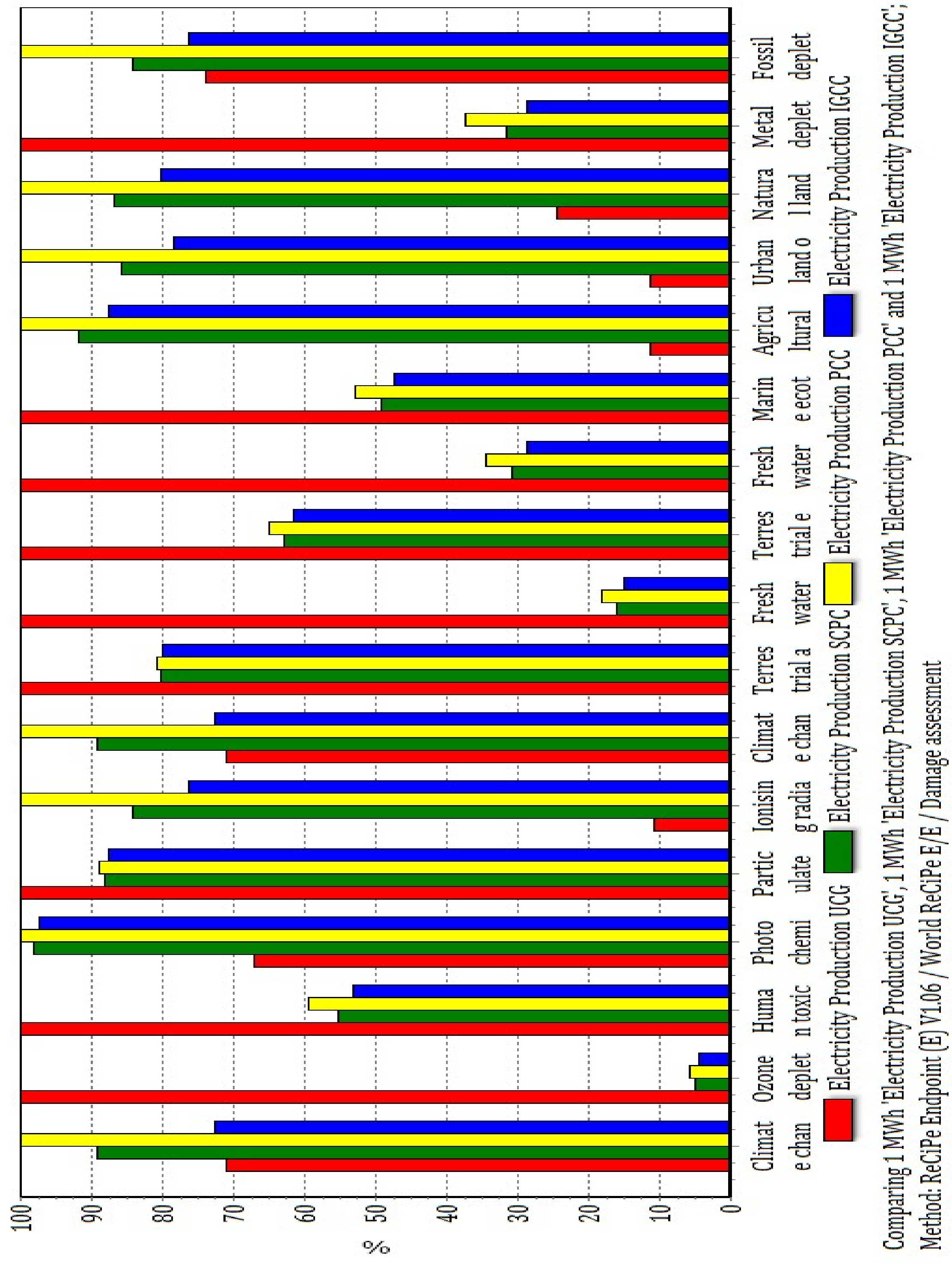
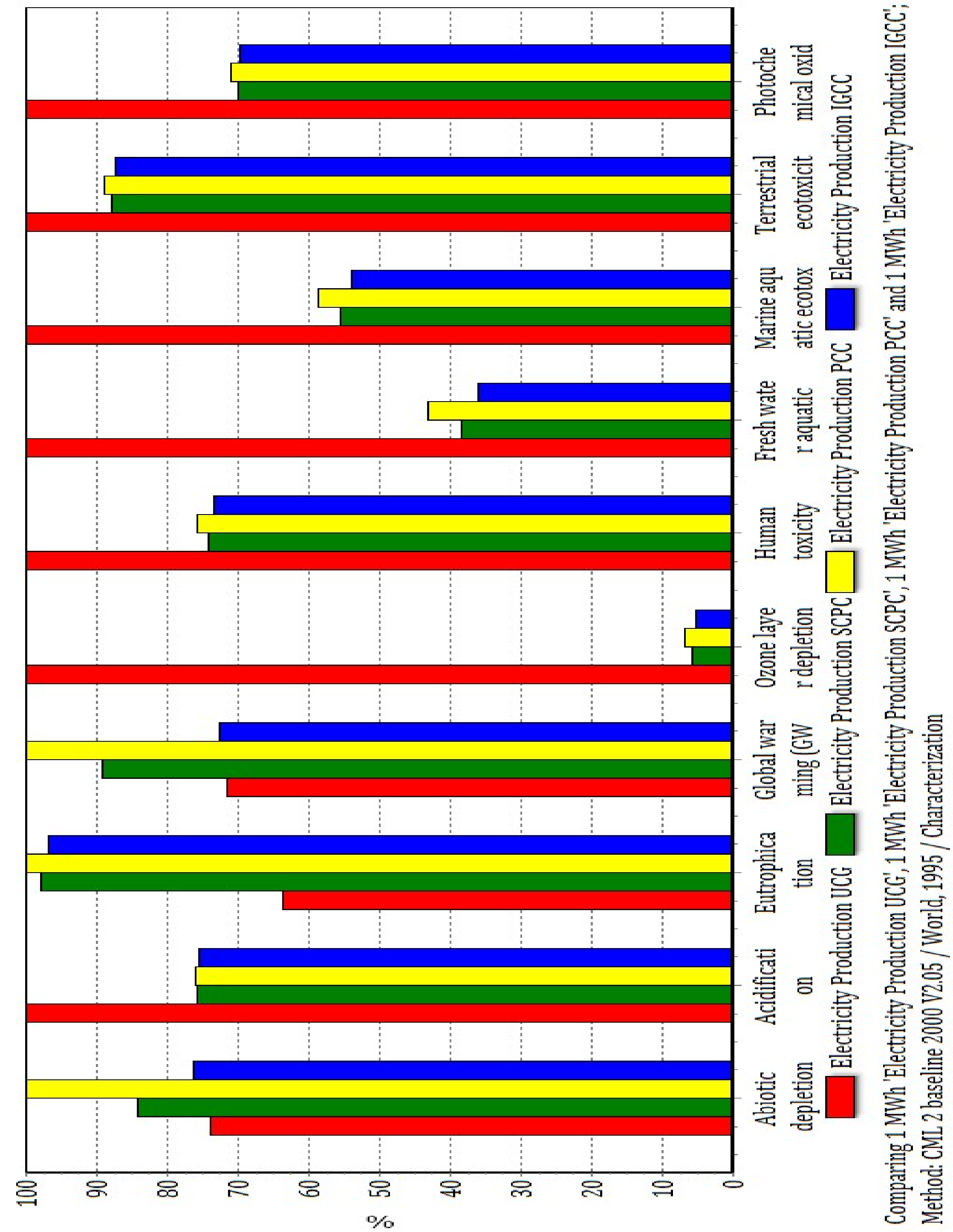


Figure S: Environmental damage assessment based on recipe endpoint method

Appendix Y: Characterization based on CML 2000 baseline/ World 1995



Comparing 1 MWh 'Electricity Production UCG', 1 MWh 'Electricity Production SCPC', 1 MWh 'Electricity Production PCC' and 1 MWh 'Electricity Production IGCC';
Method: CML 2 baseline 2000 V2.05 / World, 1995 / Characterization

Figure T: Characterization based on CML 2000 method

Appendix Z: Inventory Results

SimaPro 7.3	*Inventory*	*Date: 8/15/2012*	*Time: 3:15 PM*
Project	LCA of Electricity Production		
Calculation:	Compare		
Results:	Inventory		
Product 1:	1 MWh Electricity Production by UCG-IGCC		
Product 2:	1 MWh Electricity Production by SPSC		
Product 3:	1 MWh Electricity Production by Coal-IGCC		
Product 4:	1 MWh Electricity Production by PCC		
Method:	IPCC 2007 GWP 100a V1.02		
Indicator:	Inventory		
Unit:	All		
Default units:	Yes		
Exclude long-term emissions:	No		
Sorted on item:	Main category		
Sort order:	Descending		

No	**Substance**	**Compartment**	**Unit**	**Electricity Production UCG**	**Electricity Production SPSC**	**Electricity Production IGCC**	**Electricity Production PCC**
1	Zinc	Soil	mg	0.69	3.68	3.34	4.37
2	Vanadium	Soil	µg	0.44	1.72	1.55	2.03
3	Titanium	Soil	µg	15.30	59.96	54.31	71.09
4	Tin	Soil	ng	123.72	66.74	60.81	78.42
5	Thiram	Soil	ng	116.22	12.13	10.98	14.39
6	Teflubenzuron	Soil	ng	135.31	21.66	19.98	24.98
7	Tebutam	Soil	µg	0.10	1.04	0.94	1.23
8	Sulfuric acid	Soil	pg	73.31	160.82	145.79	190.40
9	Sulfur	Soil	mg	20.80	76.72	69.44	91.05
10	Strontium	Soil	mg	0.34	1.28	1.16	1.52
11	Sodium	Soil	mg	68.82	256.10	231.80	303.95

12	Silicon	Soil	mg	4.53	16.41	14.85	19.46
13	Potassium	Soil	mg	12.62	46.86	42.41	55.61
14	Pirimicarb	Soil	ng	7.01	347.51	315.02	411.47
15	Phosphorus	Soil	mg	1.83	6.78	6.14	8.05
16	Orbencarb	Soil	µg	10.96	1.75	1.62	2.02
17	Oils, unspecified	Soil	g	0.64	19.49	17.64	23.14
18	Oils, biogenic	Soil	mg	0.51	116.29	105.30	137.94
19	Nickel	Soil	µg	2.09	10.86	9.84	12.86
20	Napropamide	Soil	ng	43.84	438.76	397.83	519.34
21	Molybdenum	Soil	ng	69.18	176.22	159.69	208.75
22	Metribuzin	Soil	µg	2.03	0.32	0.30	0.37
23	Metolachlor	Soil	µg	8.10	401.40	363.87	475.27
24	Metaldehyde	Soil	ng	24.78	248.00	224.87	293.55
25	Mercury	Soil	ng	21.09	57.87	52.50	68.43
26	Manganese	Soil	mg	1.60	5.96	5.40	7.07
27	Mancozeb	Soil	µg	57.64	9.23	8.51	10.64
28	Magnesium	Soil	mg	27.86	103.12	93.34	122.39
29	Linuron	Soil	µg	1.12	55.46	50.27	65.67
30	Lead	Soil	µg	3.89	29.12	26.38	34.50
31	Iron	Soil	g	0.09	20.12	18.20	23.89
32	Heat, waste	Soil	kJ	11.98	81.96	74.24	97.16
33	Glyphosate	Soil	mg	0.08	10.59	9.58	12.57
34	Fluoride	Soil	mg	1.80	6.92	6.27	8.22
35	Fenpiclonil	Soil	µg	1.75	0.53	0.48	0.62
36	Cypermethrin	Soil	µg	5.07	0.56	0.51	0.66
37	Copper	Soil	µg	81.92	577.91	523.51	685.02
38	Cobalt	Soil	ng	247.17	808.18	732.14	957.89
39	Chromium VI	Soil	µg	123.58	840.47	761.33	996.28
40	Chromium	Soil	µg	174.85	651.02	589.25	772.62
41	Chlorothalonil	Soil	µg	44.38	7.11	6.55	8.19
42	Chloride	Soil	g	0.17	1.04	0.94	1.23
43	Carbon	Soil	mg	104.29	383.44	347.05	455.07
44	Carbofuran	Soil	µg	35.91	3.75	3.39	4.45
45	Carbetamide	Soil	µg	0.07	1.31	1.19	1.55
46	Calcium	Soil	mg	140.82	521.36	471.89	618.75
47	Cadmium	Soil	µg	0.26	1.65	1.49	1.95
48	Boron	Soil	mg	0.37	1.42	1.29	1.69

49	Bentazone	Soil	µg	0.07	3.67	3.33	4.35
50	Benomyl	Soil	ng	65.51	6.84	6.19	8.11
51	Barium	Soil	mg	17.17	63.56	57.53	75.43
52	Atrazine	Soil	pg	381.78	839.06	760.66	993.41
53	Arsenic	Soil	µg	13.83	51.16	46.31	60.72
54	Antimony	Soil	ng	2.82	0.86	0.79	1.02
55	Aluminium	Soil	mg	34.66	128.12	115.96	152.05
56	Aldrin	Soil	ng	1.46	3.20	2.90	3.79
57	Aclonifen	Soil	µg	0.15	7.20	6.53	8.52
58	2,4-D	Soil	µg	10.28	1.07	0.97	1.27
59	Zirconium-95	Water	µBq	10.28	423.98	383.72	503.24
60	Zinc, ion	Water	g	11.95	0.52	0.48	0.60
61	Zinc-65	Water	mBq	0.89	36.61	33.14	43.46
62	Zinc	Water	mg	27.50	19.88	17.99	23.61
63	Yttrium	Water	µg	99.55	77.22	69.86	91.70
64	Xylene	Water	mg	13.52	37.65	34.07	44.69
65	VOC, volatile organic compounds, unspecified origin	Water	mg	3.46	96.01	86.90	113.94
66	Vanadium, ion	Water	mg	110.60	153.47	148.99	162.30
67	Vanadium	Water	µg	401.12	311.15	281.51	369.49
68	Urea	Water	ng	6.65	2.58	2.36	3.02
69	Uranium alpha	Water	Bq	0.95	7.40	6.70	8.78
70	Uranium-238	Water	mBq	220.18	510.16	462.00	604.98
71	Uranium-235	Water	mBq	32.76	254.40	230.37	301.73
72	Uranium-234	Water	mBq	19.85	154.19	139.62	182.87
73	Tungsten	Water	mg	305.90	11.41	10.88	12.45
74	Trimethylamine	Water	pg	22.06	818.43	741.91	969.06
75	Triethylene glycol	Water	mg	3.76	0.12	0.11	0.14
76	Tributyltin compounds	Water	µg	27.23	317.08	287.16	375.99
77	Toluene, 2-chloro-	Water	ng	20.40	6.30	5.72	7.44
78	Toluene	Water	mg	24.65	52.82	47.80	62.70
79	TOC, Total Organic Carbon	Water	g	1.80	19.75	17.88	23.44
80	Titanium, ion	Water	g	0.22	1.41	1.38	1.47
81	Tin, ion	Water	mg	202.49	7.80	7.41	8.56
82	Tin	Water	mg	2.98	2.12	1.92	2.51

83	Thorium-234	Water	mBq	16.55	128.50	116.36	152.41
84	Thorium-232	Water	mBq	3.76	15.56	14.10	18.45
85	Thorium-230	Water	Bq	2.26	17.53	15.87	20.79
86	Thorium-228	Water	Bq	1.96	54.68	49.50	64.90
87	Thallium	Water	mg	21.05	1.94	1.89	2.05
88	Tetradecane	Water	µg	358.05	277.74	251.28	329.81
89	Tellurium-132	Water	µBq	0.50	20.67	18.70	24.53
90	Tellurium-123m	Water	mBq	0.19	1.38	1.25	1.64
91	Technetium-99m	Water	mBq	0.20	8.20	7.43	9.74
92	Tar	Water	ng	2.15	3.25	2.94	3.86
93	t-Butylamine	Water	ng	0.62	9.08	8.23	10.75
94	t-Butyl methyl ether	Water	µg	19.66	588.91	533.00	698.99
95	Suspended solids, unspecified	Water	g	71.84	29.67	27.01	34.89
96	Sulfur	Water	mg	42.86	79.98	72.38	94.94
97	Sulfite	Water	mg	0.40	1.79	1.62	2.12
98	Sulfide	Water	µg	642.42	745.49	674.69	884.89
99	Sulfate	Water	oz	50.19	6.59	6.15	7.45
100	Strontium-90	Water	Bq	8.78	35.72	32.36	42.33
101	Strontium-89	Water	mBq	0.25	6.43	5.82	7.63
102	Strontium	Water	g	4.45	2.09	1.93	2.39
103	Solved solids	Water	g	658.17	511.94	463.19	607.93
104	Solids, inorganic	Water	g	0.43	1.53	1.38	1.81
105	Sodium, ion	Water	g	202.30	227.09	206.60	267.44
106	Sodium formate	Water	µg	1.17	0.43	0.39	0.50
107	Sodium-24	Water	mBq	0.07	2.70	2.44	3.21
108	Silver, ion	Water	mg	12.41	0.51	0.46	0.60
109	Silver-110	Water	mBq	12.40	292.41	264.66	347.03
110	Silver	Water	mg	31.01	24.05	21.76	28.56
111	Silicon	Water	g	53.31	151.72	146.43	162.13
112	Selenium	Water	mg	169.03	15.79	15.07	17.21
113	Scandium	Water	mg	80.33	25.09	24.66	25.92
114	Ruthenium-103	Water	µBq	1.83	75.31	68.16	89.39
115	Rubidium	Water	mg	0.10	2.73	2.47	3.24
116	Radium-228/kg	Water	pg	2.73	2.12	1.92	2.52
117	Radium-228	Water	Bq	0.98	27.34	24.75	32.45
118	Radium-226/kg	Water	pg	533.98	414.20	374.75	491.86

119	Radium-226	Water	Bq	11.44	102.03	92.38	121.03
120	Radium-224	Water	Bq	0.49	13.67	12.37	16.22
121	Radioactive species, Nuclides, unspecified	Water	Bq	160.68	275.28	249.10	326.83
122	Radioactive species, alpha emitters	Water	µBq	931.33	583.85	528.80	692.25
123	Protactinium-234	Water	mBq	16.54	128.49	116.35	152.39
124	Propylene oxide	Water	µg	11.88	114.19	103.45	135.34
125	Propylamine	Water	ng	2.31	0.75	0.68	0.87
126	Propionic acid	Water	ng	7.20	5.41	4.90	6.41
127	Propene	Water	µg	353.66	756.38	686.53	893.89
128	Propanal	Water	ng	5.77	1.87	1.71	2.18
129	Potassium, ion	Water	g	132.25	19.50	18.44	21.57
130	Potassium-40	Water	mBq	58.43	104.59	94.75	123.95
131	Polonium-210	Water	mBq	498.99	332.99	301.64	394.71
132	Phosphorus	Water	mg	0.48	2.24	2.03	2.66
133	Phosphate	Water	g	48.70	7.79	7.27	8.80
134	Phenols, unspecified	Water	mg	2.07	2.26	2.04	2.68
135	Phenol, 2,4-dimethyl-	Water	µg	413.77	320.96	290.39	381.13
136	Phenol	Water	mg	6.25	29.51	26.71	35.02
137	Phenanthrenes, alkylated, unspecified	Water	µg	4.14	2.76	2.49	3.27
138	Phenanthrene	Water	µg	3.75	2.64	2.39	3.13
139	PAH, polycyclic aromatic hydrocarbons	Water	mg	0.06	1.82	1.65	2.16
140	p-Cresol	Water	µg	458.48	355.64	321.77	422.33
141	Oils, unspecified	Water	g	2.00	19.64	17.86	23.15
142	Octadecane	Water	µg	220.30	170.89	154.61	202.93
143	o-Xylene	Water	ng	1.04	4.30	3.90	5.11
144	o-Cresol	Water	µg	424.94	329.63	298.23	391.43
145	Nitrogen, total	Water	mg	2.65	3.99	3.61	4.74
146	Nitrogen, organic bound	Water	mg	149.09	32.77	29.69	38.82
147	Nitrogen	Water	mg	4.08	20.80	18.84	24.67
148	Nitrobenzene	Water	ng	132.22	33.75	30.66	39.84
149	Nitrite	Water	µg	193.77	414.72	375.60	491.74
150	Nitric acid	Water	µg	85.52	129.13	116.83	153.34
151	Nitrate compounds	Water	ng	38.13	57.57	52.09	68.36

152	Nitrate	Water	g	3.58	2.01	1.88	2.27
153	Niobium-95	Water	mBq	0.16	1.79	1.62	2.12
154	Nickel, ion	Water	mg	427.19	363.22	337.05	414.76
155	Nickel	Water	mg	3.76	2.75	2.49	3.27
156	Naphthalenes, alkylated, unspecified	Water	µg	9.98	6.65	6.02	7.90
157	Naphthalene, 2-methyl-	Water	µg	233.98	181.49	164.21	215.52
158	Naphthalene	Water	µg	269.00	208.55	188.69	247.66
159	n-Hexacosane	Water	µg	9.86	7.65	6.92	9.08
160	Molybdenum-99	Water	µBq	8.65	356.93	323.03	423.65
161	Molybdenum	Water	mg	222.31	24.83	23.81	26.84
162	Methyl formate	Water	pg	420.10	321.50	292.26	379.06
163	Methyl ethyl ketone	Water	µg	1.19	0.92	0.83	1.10
164	Methyl amine	Water	ng	7.71	5.24	4.75	6.21
165	Methyl acrylate	Water	µg	1.25	2.75	2.49	3.25
166	Methyl acetate	Water	pg	11.97	462.45	419.21	547.56
167	Methanol	Water	mg	4.55	0.19	0.17	0.23
168	Methane, monochloro-, R-40	Water	ng	594.57	461.21	417.28	547.68
169	Methane, dichloro-, HCC-30	Water	mg	0.87	3.22	2.91	3.82
170	Metallic ions, unspecified	Water	ng	131.97	199.27	180.29	236.63
171	Mercury	Water	µg	784.24	713.67	662.98	813.47
172	Manganese-54	Water	mBq	1.03	20.94	18.96	24.86
173	Manganese	Water	g	28.33	2.01	1.87	2.28
174	Magnesium	Water	g	244.63	33.86	31.47	38.55
175	m-Xylene	Water	µg	447.56	347.17	314.11	412.27
176	Lithium, ion	Water	g	3.20	4.31	3.90	5.11
177	Lead-210/kg	Water	pg	1.53	1.19	1.08	1.41
178	Lead-210	Water	mBq	332.54	241.18	218.48	285.88
179	Lead	Water	mg	182.66	17.61	16.04	20.70
180	Lanthanum-140	Water	mBq	0.03	1.04	0.94	1.23
181	Lactic acid	Water	ng	13.14	2.86	2.60	3.37
182	Isopropylamine	Water	ng	0.40	1.79	1.63	2.12
183	Iron, ion	Water	g	82.95	6.89	6.40	7.86
184	Iron-59	Water	µBq	4.07	167.75	151.82	199.11

185	Iron	Water	g	5.07	1.69	1.53	2.01
186	Iodine-133	Water	µBq	14.79	610.15	552.22	724.22
187	Iodine-131	Water	mBq	0.34	4.34	3.93	5.15
188	Iodide	Water	mg	1.00	30.99	28.39	36.11
189	Hypochlorite	Water	µg	146.45	655.79	594.32	776.81
190	Hydroxide	Water	µg	4.39	10.33	9.36	12.23
191	Hydrogen sulfide	Water	mg	4.51	3.14	2.91	3.59
192	Hydrogen peroxide	Water	µg	3.93	4.47	4.10	5.20
193	Hydrogen-3, Tritium	Water	kBq	2.77	18.64	16.88	22.11
194	Hydrocarbons, unspecified	Water	mg	20.67	21.30	19.29	25.27
195	Hydrocarbons, aromatic	Water	mg	6.67	145.92	132.07	173.17
196	Hydrocarbons, aliphatic, unsaturated	Water	mg	0.12	3.28	2.97	3.89
197	Hydrocarbons, aliphatic, alkanes, unspecified	Water	mg	1.27	35.54	32.17	42.18
198	Hexanoic acid	Water	mg	3.10	2.41	2.18	2.86
199	Hexadecane	Water	µg	891.73	691.71	625.83	821.40
200	Heat, waste	Water	MJ	0.59	11.30	10.85	12.18
201	Glutaraldehyde	Water	µg	127.93	124.96	113.10	148.30
202	Formic acid	Water	ng	2.12	0.69	0.63	0.80
203	Formate	Water	µg	0.08	1.17	1.06	1.38
204	Formamide	Water	ng	7.29	2.36	2.16	2.76
205	Formaldehyde	Water	µg	54.27	163.03	147.79	193.02
206	Fluosilicic acid	Water	µg	87.61	752.54	681.71	891.98
207	Fluorine	Water	µg	17.59	11.85	10.72	14.07
208	Fluoride	Water	g	17.95	0.57	0.52	0.66
209	Fluorenes, alkylated, unspecified	Water	µg	35.31	23.51	21.27	27.92
210	Fluorene, 1-methyl-	Water	µg	1.68	1.30	1.18	1.55
211	Ethylene oxide	Water	ng	79.78	401.79	364.62	474.97
212	Ethylene diamine	Water	ng	97.74	19.79	18.18	22.95
213	Ethylamine	Water	ng	4.73	4.60	4.19	5.43
214	Ethyl acetate	Water	ng	28.05	16.40	14.86	19.43
215	Ethene, chloro-	Water	µg	0.23	1.38	1.25	1.64
216	Ethene	Water	µg	354.67	709.50	642.56	841.29
217	Ethanol	Water	µg	1.03	2.96	2.68	3.50

218	Ethane, 1,2-dichloro-	Water	µg	5.61	6.08	5.51	7.21
219	Eicosane	Water	µg	224.93	174.48	157.86	207.20
220	Dodecane	Water	µg	816.98	633.72	573.37	752.55
221	Docosane	Water	µg	15.81	12.26	11.09	14.56
222	DOC, Dissolved Organic Carbon	Water	g	1.80	19.72	17.85	23.40
223	Dipropylamine	Water	ng	16.78	3.65	3.32	4.31
224	Dimethylamine	Water	ng	11.58	39.67	35.96	46.96
225	Diethylamine	Water	ng	26.30	6.75	6.13	7.97
226	Dichromate	Water	µg	3.23	21.91	19.84	25.97
227	Dibenzothiophene	Water	µg	2.40	1.85	1.67	2.19
228	Dibenzofuran	Water	µg	2.81	2.18	1.97	2.59
229	Detergent, oil	Water	mg	12.79	10.20	9.23	12.11
230	Decane	Water	µg	430.59	334.01	302.20	396.63
231	Cyanide	Water	mg	30.78	2.87	2.61	3.39
232	Cumene	Water	mg	0.91	1.78	1.62	2.10
233	Copper, ion	Water	g	1.77	0.08	0.07	0.09
234	COD, Chemical Oxygen Demand	Water	g	9.94	67.41	61.01	79.99
235	Cobalt-60	Water	mBq	13.37	302.51	273.81	359.02
236	Cobalt-58	Water	mBq	16.64	346.00	313.18	410.61
237	Cobalt-57	Water	mBq	0.05	2.19	1.98	2.60
238	Cobalt	Water	mg	612.77	83.01	76.80	95.23
239	Chromium, ion	Water	mg	3.73	4.39	3.97	5.21
240	Chromium VI	Water	mg	123.60	170.21	156.62	196.96
241	Chromium-51	Water	mBq	2.54	75.05	67.92	89.07
242	Chromium	Water	mg	28.23	17.83	16.13	21.18
243	Chlorosulfonic acid	Water	ng	0.33	14.34	13.00	16.97
244	Chloroform	Water	ng	9.15	17.76	16.11	21.02
245	Chloroacetyl chloride	Water	ng	0.07	1.55	1.41	1.84
246	Chloroacetic acid	Water	µg	2.09	112.21	101.66	132.97
247	Chlorine	Water	µg	28.94	187.66	178.03	206.61
248	Chlorinated solvents, unspecified	Water	µg	3.14	5.65	5.13	6.68
249	Chloride	Water	g	543.44	596.63	542.97	702.27
250	Chlorate	Water	mg	6.44	6.39	5.82	7.51
251	Chloramine	Water	ng	52.30	25.93	23.64	30.44

252	Cesium-137	Water	Bq	1.21	8.19	7.42	9.72
253	Cesium-136	Water	µBq	1.67	68.97	62.42	81.86
254	Cesium-134	Water	mBq	1.51	9.74	8.82	11.55
255	Cesium	Water	µg	9.76	273.41	247.47	324.48
256	Cerium-144	Water	µBq	2.87	118.30	107.07	140.42
257	Cerium-141	Water	µBq	9.42	388.59	351.69	461.24
258	Carboxylic acids, unspecified	Water	g	0.05	1.18	1.07	1.40
259	Carbonate	Water	mg	0.57	1.62	1.47	1.91
260	Carbon disulfide	Water	ng	192.41	34.33	31.61	39.70
261	Calcium, ion	Water	g	433.87	91.43	83.92	106.23
262	Cadmium, ion	Water	mg	225.53	6.44	5.91	7.48
263	Butyrolactone	Water	ng	0.82	1.84	1.67	2.18
264	Butyl acetate	Water	µg	0.48	1.07	0.97	1.26
265	Butene	Water	ng	163.02	364.39	330.35	431.41
266	Bromine	Water	mg	12.75	238.56	220.00	275.09
267	Bromide	Water	g	3.16	2.46	2.22	2.92
268	Bromate	Water	µg	785.31	798.91	728.09	938.32
269	Boron	Water	g	9.78	0.28	0.26	0.33
270	Borate	Water	ng	304.10	144.81	132.03	169.96
271	BOD5, Biological Oxygen Demand	Water	g	6.16	62.41	56.48	74.07
272	Biphenyl	Water	µg	39.45	26.27	23.77	31.20
273	Beryllium	Water	mg	46.26	6.18	5.92	6.69
274	Benzoic acid	Water	mg	14.98	11.62	10.52	13.80
275	Benzenes, alkylated, unspecified	Water	µg	609.30	405.75	367.11	481.83
276	Benzene, pentamethyl-	Water	µg	1.11	0.86	0.78	1.02
277	Benzene, ethyl-	Water	mg	1.63	7.64	6.92	9.07
278	Benzene, chloro-	Water	µg	3.57	8.35	7.57	9.88
279	Benzene, 1,2-dichloro-	Water	ng	180.06	438.68	397.72	519.31
280	Benzene, 1-methyl-4-(1-methylethyl)-	Water	µg	1.48	1.15	1.04	1.36
281	Benzene	Water	mg	26.35	39.41	35.67	46.78
282	Barium-140	Water	mBq	0.02	0.97	0.88	1.15
283	Barium	Water	g	15.44	10.62	9.61	12.60
284	Barite	Water	g	1.04	1.01	0.92	1.20

285	Arsenic, ion	Water	mg	355.81	64.18	62.42	67.65
286	AOX, Adsorbable Organic Halogen as Cl	Water	µg	24.26	248.14	225.14	293.41
287	Antimony-125	Water	mBq	1.70	18.06	16.35	21.42
288	Antimony-124	Water	mBq	1.81	18.95	17.15	22.48
289	Antimony-122	Water	µBq	5.38	221.88	200.81	263.36
290	Antimony	Water	mg	113.23	9.22	8.89	9.87
291	Aniline	Water	ng	59.23	14.15	12.86	16.70
292	Ammonium, ion	Water	mg	8.96	37.50	34.14	44.12
293	Ammonia, as N	Water	µg	1.41	2.13	1.93	2.53
294	Ammonia	Water	mg	263.92	195.10	176.52	231.69
295	Aluminium	Water	g	31.14	28.31	27.89	29.13
296	Actinides, radioactive, unspecified	Water	mBq	10.51	70.36	63.72	83.44
297	Acrylate, ion	Water	ng	133.81	293.55	266.12	347.55
298	Acids, unspecified	Water	µg	2.81	4.25	3.84	5.04
299	Acidity, unspecified	Water	µg	549.68	68.12	61.76	80.64
300	Acetyl chloride	Water	ng	3.13	1.01	0.93	1.19
301	Acetonitrile	Water	ng	0.09	3.94	3.57	4.67
302	Acetone	Water	µg	147.73	114.97	104.02	136.53
303	Acetic acid	Water	µg	78.41	411.32	372.30	488.12
304	Acetaldehyde	Water	µg	0.98	16.62	15.04	19.73
305	Acenaphthylene	Water	ng	3.80	106.36	96.27	126.23
306	Acenaphthene	Water	µg	0.06	1.70	1.54	2.02
307	4-Methyl-2-pentanone	Water	µg	62.08	48.15	43.57	57.18
308	2-Propanol	Water	ng	0.92	4.14	3.75	4.90
309	2-Methyl-2-butene	Water	pg	0.67	0.22	0.20	0.25
310	2-Methyl-1-propanol	Water	ng	8.53	3.52	3.20	4.13
311	2-Hexanone	Water	µg	96.45	74.82	67.69	88.85
312	2-Aminopropanol	Water	ng	0.06	1.16	1.05	1.38
313	1,4-Butanediol	Water	ng	2.63	1.93	1.75	2.28
314	1-Propanol	Water	ng	5.46	7.38	6.71	8.72
315	1-Pentene	Water	ng	3.01	0.98	0.89	1.14
316	1-Pentanol	Water	ng	3.99	1.29	1.18	1.51
317	1-Butanol	Water	ng	371.90	821.37	744.62	972.49
318	Zirconium-95	Air	µBq	0.35	14.51	13.13	17.22
319	Zirconium	Air	µg	4.46	12.95	11.75	15.31

320	Zinc-65	Air	µBq	0.36	14.84	13.43	17.61
321	Zinc	Air	mg	60.53	27.17	24.89	31.64
322	Xylene	Air	mg	3.62	205.40	188.99	237.71
323	Xenon-138	Air	Bq	0.42	14.06	12.73	16.69
324	Xenon-137	Air	Bq	0.05	1.86	1.69	2.21
325	Xenon-135m	Air	Bq	2.25	61.43	55.60	72.91
326	Xenon-135	Air	Bq	3.76	98.10	88.79	116.43
327	Xenon-133m	Air	mBq	32.35	324.18	293.50	384.58
328	Xenon-133	Air	Bq	9.21	244.64	221.42	290.34
329	Xenon-131m	Air	Bq	0.28	6.78	6.14	8.05
330	Water	Air	g	2.86	0.39	0.36	0.45
331	VOC, volatile organic compounds	Air	g	9.88	12.41	11.23	14.74
332	Vinyl acetate	Air	ng	520.81	597.74	540.81	709.82
333	Vanadium	Air	mg	3.10	6.88	6.32	7.96
334	Uranium alpha	Air	mBq	48.76	378.66	342.88	449.10
335	Uranium-238	Air	Bq	0.02	1.05	1.04	1.07
336	Uranium-235	Air	mBq	0.51	3.93	3.56	4.66
337	Uranium-234	Air	mBq	11.95	81.95	74.21	97.20
338	Uranium	Air	µg	0.75	3.17	2.94	3.64
339	Tungsten	Air	µg	1.23	9.53	8.63	11.30
340	Trimethylamine	Air	pg	9.19	341.02	309.14	403.79
341	Toluene, 2,4-dinitro-	Air	ng	19.19	22.02	19.92	26.15
342	Toluene, 2-chloro-	Air	ng	9.76	3.45	3.13	4.07
343	Toluene	Air	mg	3.79	186.87	169.47	221.13
344	Titanium	Air	mg	0.35	2.12	1.93	2.50
345	Tin	Air	mg	9.27	0.33	0.30	0.38
346	Thorium-234	Air	mBq	0.90	6.98	6.32	8.27
347	Thorium-232	Air	mBq	3.17	294.09	292.86	296.53
348	Thorium-230	Air	mBq	4.83	26.67	24.15	31.64
349	Thorium-228	Air	mBq	2.74	190.50	189.47	192.53
350	Thorium	Air	µg	0.79	3.03	2.79	3.50
351	Thallium	Air	µg	0.88	8.46	7.71	9.94
352	Terpenes	Air	µg	25.53	2.66	2.41	3.16
353	Tar	Air	ng	150.64	227.45	205.79	270.09
354	t-Butylamine	Air	ng	0.26	3.78	3.43	4.48
355	t-Butyl methyl ether	Air	µg	3.23	7.20	6.59	8.39

356	Sulfuric acid, dimethyl ester	Air	µg	3.29	3.78	3.42	4.48
357	Sulfuric acid	Air	ng	119.23	263.81	239.16	312.34
358	Sulfur trioxide	Air	ng	265.09	71.51	64.96	84.42
359	Sulfur oxides	Air	oz	116.55	0.41	0.37	0.48
360	Sulfur hexafluoride	Air	µg	32.22	162.63	147.46	192.50
361	Sulfur dioxide	Air	kg	6.87	6.94	6.93	6.97
362	Sulfate	Air	mg	35.38	50.88	46.09	60.32
363	Styrene	Air	µg	5.62	24.13	21.85	28.62
364	Strontium	Air	mg	0.10	4.42	4.38	4.50
365	Sodium hydroxide	Air	µg	0.57	1.25	1.13	1.48
366	Sodium formate	Air	ng	488.67	177.27	161.36	208.59
367	Sodium dichromate	Air	µg	0.88	5.91	5.35	7.00
368	Sodium chlorate	Air	µg	8.83	4.75	4.30	5.63
369	Sodium	Air	mg	1.39	6.92	6.28	8.17
370	Silver-110	Air	nBq	18.62	768.22	695.27	911.84
371	Silver	Air	µg	0.48	3.71	3.36	4.40
372	Silicon tetrafluoride	Air	ng	823.09	448.06	405.86	531.15
373	Silicon	Air	mg	7.42	30.13	27.69	34.93
374	Selenium	Air	mg	297.67	291.55	291.17	292.29
375	Scandium	Air	µg	11.50	86.68	78.52	102.74
376	Ruthenium-103	Air	nBq	1.88	77.51	70.15	92.01
377	Radon-222	Air	kBq	118.60	921.03	834.01	1092.36
378	Radon-220	Air	Bq	0.35	24.66	24.52	24.94
379	Radium-228	Air	mBq	17.40	410.67	404.72	422.37
380	Radium-226	Air	Bq	0.04	1.40	1.37	1.45
381	Radionuclides (Including Radon)	Air	mg	133.14	201.02	181.88	238.71
382	Radioactive species, unspecified	Air	kBq	12597.90	12647.41	12633.37	12675.05
383	Radioactive species, other beta emitters	Air	mBq	46.07	506.96	459.26	600.88
384	Pyrene	Air	µg	73.50	73.79	73.71	73.96
385	Protactinium-234	Air	mBq	0.90	6.97	6.32	8.27
386	Propylene oxide	Air	µg	4.94	47.46	42.99	56.25
387	Propylamine	Air	pg	962.47	311.60	284.89	364.19
388	Propionic acid	Air	µg	36.48	116.57	105.65	138.07

389	Propene	Air	mg	11.58	25.71	23.33	30.38
390	Propane	Air	mg	926.52	272.12	246.48	322.61
391	Propanal	Air	µg	26.24	30.87	27.94	36.65
392	Potassium-40	Air	Bq	0.01	1.11	1.11	1.12
393	Potassium	Air	mg	3.08	13.82	12.55	16.32
394	Polychlorinated biphenyls	Air	µg	3.95	12.48	11.33	14.76
395	Polonium-210	Air	Bq	0.08	8.29	8.26	8.36
396	Plutonium-alpha	Air	nBq	2.02	13.55	12.27	16.06
397	Plutonium-238	Air	nBq	0.88	5.91	5.35	7.01
398	Platinum	Air	pg	94.79	660.17	597.81	782.95
399	Phthalate, dioctyl-	Air	µg	5.00	5.74	5.19	6.82
400	Phosphorus	Air	µg	74.19	261.55	238.47	306.99
401	Phosphine	Air	pg	48.87	107.21	97.20	126.93
402	Phenols, unspecified	Air	mg	4.90	4.05	4.00	4.14
403	Phenol, pentachloro-	Air	µg	1.70	6.91	6.26	8.19
404	Phenol, 2,4-dichloro-	Air	ng	2.96	1.13	1.02	1.34
405	Phenol	Air	µg	51.66	222.66	204.61	258.18
406	Phenanthrene	Air	µg	601.35	603.75	603.06	605.11
407	Pentane	Air	mg	14.36	331.67	300.73	392.59
408	Particulates, unspecified	Air	g	517.58	593.44	536.92	704.71
409	Particulates, SPM	Air	g	957.80	x	x	x
410	Particulates, > 2.5 um, and < 10um	Air	g	45.56	52.88	52.22	54.19
411	Particulates, > 10 um	Air	g	1.70	19.34	18.38	21.24
412	Particulates, < 2.5 um	Air	g	2.64	42.18	41.56	43.41
413	PAH, polycyclic aromatic hydrocarbons	Air	mg	1.22	2.70	2.45	3.19
414	Ozone	Air	mg	2.66	14.42	13.06	17.09
415	Organic substances, unspecified	Air	g	1.35	1.35	1.35	1.36
416	Organic acids	Air	µg	18.27	27.58	24.96	32.75
417	Noble gases, radioactive, unspecified	Air	kBq	62.18	416.25	376.95	493.62
418	NMVOC, non-methane volatile organic compounds, unspecified	Air	g	36.89	53.25	50.56	58.55

	origin						
419	Nitrogen oxides	Air	kg	1.64	3.03	3.00	3.08
420	Nitrobenzene	Air	ng	32.99	8.42	7.65	9.94
421	Nitrate	Air	µg	118.60	282.51	256.04	334.63
422	Niobium-95	Air	nBq	8.55	352.81	319.31	418.76
423	Nickel	Air	mg	212.25	75.24	74.09	77.49
424	Naphthalene	Air	mg	2.97	2.99	2.98	3.01
425	Monoethanolamine	Air	µg	7.14	29.59	27.09	34.53
426	Molybdenum	Air	µg	26.08	223.89	210.09	251.06
427	Methyl methacrylate	Air	µg	1.37	1.57	1.42	1.87
428	Methyl lactate	Air	ng	6.01	1.31	1.19	1.54
429	Methyl formate	Air	ng	1.05	0.81	0.73	0.95
430	Methyl ethyl ketone	Air	µg	128.67	256.57	232.54	303.88
431	Methyl borate	Air	pg	616.34	232.64	212.44	272.41
432	Methyl amine	Air	ng	3.21	2.18	1.98	2.59
433	Methyl acrylate	Air	ng	64.15	140.72	127.58	166.61
434	Methyl acetate	Air	pg	4.99	192.69	174.67	228.15
435	Methanol	Air	mg	1.90	2.85	2.59	3.38
436	Methanesulfonic acid	Air	ng	0.11	4.76	4.31	5.63
437	Methane, trifluoro-, HFC-23	Air	ng	6.43	17.51	15.87	20.72
438	Methane, trichlorofluoro-, CFC-11	Air	pg	32.82	89.32	81.00	105.70
439	Methane, tetrafluoro-, CFC-14	Air	mg	0.37	3.22	2.92	3.82
440	Methane, tetrachloro-, CFC-10	Air	µg	8.99	5.56	5.12	6.44
441	Methane, monochloro-, R-40	Air	µg	36.34	41.84	37.86	49.69
442	Methane, fossil	Air	g	100.65	56.62	55.10	59.61
443	Methane, dichlorofluoro-, HCFC-21	Air	pg	20.21	55.02	49.89	65.11
444	Methane, dichlorodifluoro-, CFC-12	Air	µg	1.55	0.32	0.29	0.38
445	Methane, dichloro-, HCC-30	Air	mg	66.36	65.47	65.34	65.73

446	Methane, chlorodifluoro-, HCFC-22	Air	mg	19.41	0.05	0.04	0.05
447	Methane, bromotrifluoro-, Halon 1301	Air	µg	5.50	149.86	135.66	177.82
448	Methane, bromochlorodifluoro-, Halon 1211	Air	mg	6.24	0.01	0.01	0.01
449	Methane, bromo-, Halon 1001	Air	µg	10.96	12.58	11.39	14.94
450	Methane, biogenic	Air	mg	18.25	65.75	59.61	77.85
451	Methane	Air	kg	1.29	1.16	1.05	1.38
452	Metals, unspecified	Air	pg	496.65	749.89	678.47	890.49
453	Mercury	Air	mg	19.20	19.79	19.67	20.04
454	Mercaptans, unspecified	Air	mg	14.86	17.05	15.43	20.25
455	Manganese-54	Air	µBq	0.07	2.97	2.69	3.53
456	Manganese	Air	mg	135.36	113.81	113.49	114.44
457	Magnesium	Air	g	2.45	2.47	2.46	2.47
458	m-Xylene	Air	µg	10.57	40.65	36.81	48.19
459	Lead-210	Air	Bq	0.04	4.53	4.51	4.57
460	Lead	Air	mg	279.73	103.67	102.88	105.23
461	Lanthanum-140	Air	µBq	0.77	31.93	28.90	37.90
462	Lactic acid	Air	ng	5.48	1.19	1.08	1.41
463	Krypton-89	Air	mBq	18.30	680.75	616.11	808.00
464	Krypton-88	Air	Bq	0.06	1.67	1.52	1.99
465	Krypton-87	Air	Bq	0.06	1.32	1.19	1.56
466	Krypton-85m	Air	Bq	0.17	5.54	5.01	6.57
467	Krypton-85	Air	Bq	2.52	11.00	9.97	13.04
468	Kerosene	Air	mg	2.38	3.59	3.25	4.27
469	Isopropylamine	Air	pg	166.21	747.14	677.55	884.15
470	Isoprene	Air	g	4.39	6.63	6.00	7.87
471	Isophorone	Air	µg	39.75	45.62	41.27	54.17
472	Isocyanic acid	Air	mg	0.00	1.18	1.07	1.40
473	Iron	Air	mg	7.01	38.37	34.87	45.26
474	Iodine-135	Air	µBq	17.51	150.84	136.58	178.93
475	Iodine-133	Air	µBq	18.90	516.26	467.27	612.72
476	Iodine-131	Air	Bq	0.32	1.29	1.17	1.53

477	Iodine-129	Air	mBq	6.47	43.32	39.23	51.37
478	Iodine	Air	mg	0.13	10.97	10.92	11.07
479	Indeno(1,2,3-cd)pyrene	Air	µg	13.59	13.64	13.63	13.67
480	Hydrogen sulfide	Air	mg	166.50	23.48	21.30	27.76
481	Hydrogen peroxide	Air	ng	152.39	335.73	304.36	397.49
482	Hydrogen fluoride	Air	g	33.41	33.67	33.62	33.75
483	Hydrogen chloride	Air	g	267.53	269.63	269.31	270.28
484	Hydrogen-3, Tritium	Air	Bq	36.97	235.72	213.48	279.51
485	Hydrogen	Air	mg	21.70	12.69	11.51	15.03
486	Hydrocarbons, unspecified	Air	mg	28.69	43.32	39.19	51.44
487	Hydrocarbons, chlorinated	Air	µg	31.01	185.45	167.97	219.86
488	Hydrocarbons, aromatic	Air	mg	42.67	30.88	28.02	36.50
489	Hydrocarbons, aliphatic, unsaturated	Air	mg	0.90	11.17	10.85	11.78
490	Hydrocarbons, aliphatic, alkanes, unspecified	Air	mg	95.98	121.02	110.51	141.70
491	Hydrocarbons, aliphatic, alkanes, cyclic	Air	µg	17.68	15.07	13.65	17.87
492	Hydrazine, methyl-	Air	µg	11.65	13.37	12.10	15.88
493	Hexane	Air	mg	6.19	125.88	113.94	149.37
494	Heptane	Air	mg	2.01	57.32	51.88	68.02
495	Helium	Air	mg	0.55	10.91	9.88	12.94
496	Heat, waste	Air	MJ	269.73	266.49	243.79	311.19
497	Furan	Air	µg	59.28	7.18	6.61	8.32
498	Formic acid	Air	µg	205.01	21.67	19.61	25.70
499	Formamide	Air	ng	3.04	0.98	0.90	1.15
500	Formaldehyde	Air	mg	63.15	85.60	82.72	91.26
501	Fluosilicic acid	Air	µg	48.67	418.06	378.71	495.52
502	Fluorine	Air	mg	3.57	1.66	1.51	1.97
503	Fluoride	Air	mg	3.17	3.67	3.32	4.36
504	Fluorene	Air	µg	202.67	203.48	203.25	203.94
505	Fluoranthene	Air	µg	158.13	158.76	158.58	159.12
506	Ethyne	Air	mg	0.32	0.94	0.86	1.08
507	Ethylene oxide	Air	µg	5.39	9.76	8.84	11.57
508	Ethylene diamine	Air	ng	40.63	8.22	7.55	9.53

509	Ethylamine	Air	ng	1.97	1.92	1.74	2.26
510	Ethyl cellulose	Air	ng	205.23	450.15	408.09	532.96
511	Ethyl acetate	Air	µg	101.95	225.92	204.81	267.49
512	Ethene, tetrachloro-	Air	mg	9.61	9.63	9.61	9.65
513	Ethene, chloro-	Air	µg	18.94	106.58	96.46	126.50
514	Ethene	Air	mg	5.97	27.75	25.22	32.72
515	Ethanol	Air	µg	356.20	694.05	629.21	821.71
516	Ethane, hexafluoro-, HFC-116	Air	µg	41.83	358.15	324.45	424.52
517	Ethane, chloro-	Air	µg	2.88	3.30	2.99	3.92
518	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	µg	2.78	24.28	21.98	28.80
519	Ethane, 1,2-dichloro-	Air	µg	45.94	181.03	163.86	214.84
520	Ethane, 1,2-dibromo-	Air	ng	82.23	94.38	85.39	112.08
521	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	ng	2.68	5.89	5.34	6.97
522	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	µg	60.81	752.20	681.52	891.35
523	Ethane, 1,1,1-trichloro-, HCFC-140	Air	µg	1.68	1.78	1.61	2.11
524	Ethane, 1,1-difluoro-, HFC-152a	Air	µg	0.19	1.17	1.06	1.38
525	Ethane	Air	g	4.10	0.13	0.12	0.15
526	Dipropylamine	Air	ng	6.99	1.52	1.38	1.79
527	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	ng	182.77	184.65	183.65	186.63
528	Dinitrogen monoxide	Air	mg	401.73	648.64	588.84	766.38
529	Dimethyl malonate	Air	ng	0.13	5.90	5.35	6.99
530	Diethylamine	Air	ng	10.96	2.81	2.55	3.32
531	Cyanoacetic acid	Air	ng	0.11	4.71	4.27	5.57
532	Cyanide	Air	µg	674.13	510.46	462.39	605.11
533	Cumene	Air	µg	377.72	741.19	672.95	875.55
534	Copper	Air	mg	203.95	16.64	15.14	19.59
535	Cobalt-60	Air	µBq	1.73	71.40	64.62	84.74
536	Cobalt-58	Air	µBq	0.20	8.08	7.31	9.59
537	Cobalt	Air	mg	22.85	23.54	23.42	23.78

538	Chrysene	Air	µg	22.27	22.36	22.34	22.41
539	Chromium VI	Air	mg	17.79	18.34	18.27	18.50
540	Chromium-51	Air	µBq	0.14	5.80	5.25	6.89
541	Chromium	Air	mg	66.55	84.24	81.76	89.11
542	Chlorosulfonic acid	Air	ng	0.13	5.75	5.21	6.81
543	Chlorosilane, trimethyl-	Air	ng	110.93	690.92	635.39	800.25
544	Chloroform	Air	µg	4.18	5.63	5.09	6.68
545	Chloroacetic acid	Air	µg	0.04	13.36	12.09	15.86
546	Chlorine	Air	mg	6.58	3.31	3.00	3.92
547	Chloride	Air	ng	133.93	202.23	182.97	240.14
548	Chloramine	Air	ng	5.86	2.85	2.60	3.34
549	Cesium-137	Air	µBq	1.86	76.89	69.59	91.27
550	Cesium-134	Air	µBq	0.11	4.34	3.93	5.15
551	Cerium-141	Air	µBq	2.20	90.57	81.97	107.50
552	Carbon monoxide, fossil	Air	g	103.65	268.47	253.56	297.83
553	Carbon monoxide, biogenic	Air	mg	4.75	20.59	18.71	24.28
554	Carbon monoxide	Air	g	109.72	0.02	0.02	0.03
555	Carbon disulfide	Air	mg	762.71	21.97	20.03	25.79
556	Carbon dioxide, land transformation	Air	mg	454.03	114.30	103.52	135.51
557	Carbon dioxide, fossil	Air	kg	33.82	930.01	756.27	1041.66
558	Carbon dioxide, biogenic	Air	g	195.30	327.47	296.35	388.73
559	Carbon dioxide	Air	kg	704.96	x	x	x
560	Carbon-14	Air	Bq	6.51	53.09	48.07	62.97
561	Calcium	Air	mg	2.12	12.15	11.03	14.34
562	Cadmium	Air	mg	37.28	12.04	11.98	12.18
563	Butyrolactone	Air	pg	342.16	767.98	696.20	909.30
564	Butene	Air	mg	0.20	5.73	5.19	6.80
565	Butane	Air	mg	176.19	262.14	237.35	310.93
566	Butadiene	Air	µg	157.25	179.82	162.69	213.53
567	BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio	Air	mg	230.97	311.41	281.75	369.80
568	Bromoform	Air	µg	2.67	3.07	2.78	3.64
569	Bromine	Air	mg	0.25	21.42	21.32	21.62

570	Boron trifluoride	Air	pg	0.01	0.02	0.02	0.02
571	Boron	Air	mg	2.35	34.86	33.94	36.68
572	Biphenyl	Air	µg	378.63	380.14	379.70	380.99
573	Beryllium	Air	mg	4.83	4.73	4.73	4.75
574	Benzyl chloride	Air	µg	47.97	55.06	49.81	65.38
575	Benzo(ghi)perylene	Air	µg	0.05	6.04	6.03	6.05
576	Benzo(b,j,k)fluoranthene	Air	µg	0.20	24.60	24.57	24.65
577	Benzo(a)pyrene	Air	µg	24.55	78.85	72.26	91.81
578	Benzo(a)anthracene	Air	µg	17.82	17.89	17.87	17.93
579	Benzene, pentachloro-	Air	ng	27.05	33.08	30.01	39.13
580	Benzene, hexachloro-	Air	µg	2.27	7.46	6.77	8.82
581	Benzene, ethyl-	Air	mg	0.21	5.76	5.21	6.83
582	Benzene, chloro-	Air	µg	1.51	1.73	1.57	2.05
583	Benzene, 1,2-dichloro-	Air	ng	3.13	15.38	13.95	18.20
584	Benzene, 1-methyl-2-nitro-	Air	pg	18.59	718.59	651.41	850.85
585	Benzene	Air	mg	304.18	698.61	660.21	774.21
586	Benzaldehyde	Air	µg	0.18	0.95	0.86	1.12
587	Benzal chloride	Air	pg	0.03	0.14	0.12	0.16
588	Barium-140	Air	µBq	9.06	373.60	338.12	443.44
589	Barium	Air	mg	0.10	4.80	4.76	4.88
590	Arsine	Air	pg	0.66	1.45	1.31	1.71
591	Arsenic	Air	mg	165.22	93.50	93.27	93.95
592	Argon-41	Air	Bq	0.80	3.43	3.11	4.07
593	Antimony-125	Air	µBq	0.14	5.74	5.20	6.82
594	Antimony-124	Air	nBq	13.34	550.35	498.09	653.24
595	Antimony	Air	mg	13.21	4.21	4.20	4.24
596	Anthranilic acid	Air	pg	15.93	606.40	549.71	718.01
597	Anthracene	Air	µg	46.77	46.96	46.90	47.06
598	Aniline	Air	ng	24.67	5.76	5.23	6.79
599	Ammonium chloride	Air	mg	4.97	7.51	6.79	8.91
600	Ammonium carbonate	Air	µg	0.21	1.19	1.08	1.41
601	Ammonia	Air	mg	835.02	323.29	294.68	379.60
602	Aluminium	Air	g	1.87	0.29	0.27	0.34
603	Aldehydes, unspecified	Air	mg	346.43	297.65	289.29	314.10
604	Aerosols, radioactive, unspecified	Air	mBq	1.56	8.94	8.10	10.60

605	Actinides, radioactive, unspecified	Air	μBq	72.33	589.35	533.62	699.08
606	Acrylic acid	Air	ng	56.54	124.03	112.44	146.85
607	Acrolein	Air	mg	64.95	65.26	65.15	65.49
608	Acetophenone	Air	μg	1.03	1.18	1.07	1.40
609	Acetonitrile	Air	μg	30.63	3.20	2.89	3.79
610	Acetone	Air	μg	342.29	503.08	456.04	595.70
611	Acetic acid	Air	mg	3.00	4.89	4.43	5.80
612	Acetaldehyde	Air	mg	3.52	9.81	8.89	11.64
613	Acenaphthylene	Air	μg	55.68	55.90	55.84	56.03
614	Acenaphthene	Air	μg	0.91	114.04	113.91	114.30
615	5-methyl Chrysene	Air	μg	4.90	4.92	4.91	4.93
616	2-Propanol	Air	μg	21.84	47.88	43.41	56.69
617	2-Nitrobenzoic acid	Air	pg	21.53	832.12	754.32	985.27
618	2-Methyl-1-propanol	Air	ng	3.55	1.47	1.34	1.72
619	2-Chloroacetophenone	Air	ng	479.69	550.55	498.12	653.78
620	2-Butene, 2-methyl-	Air	pg	0.28	0.09	0.08	0.11
621	2-Aminopropanol	Air	pg	22.56	462.45	419.25	547.51
622	1,4-Butanediol	Air	ng	6.58	4.82	4.37	5.70
623	1-Propanol	Air	ng	18.86	69.70	63.18	82.54
624	1-Pentene	Air	ng	1.26	0.41	0.37	0.48
625	1-Pentanol	Air	ng	1.66	0.54	0.49	0.63
626	1-Butanol	Air	pg	806.53	637.34	577.66	754.84
627	Zirconium, 50% in zircon, 0.39% in crude ore, in ground	Raw	μg	4.83	10.65	9.66	12.61
628	Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	Raw	mg	132.45	783.21	709.16	929.00
629	Wood, unspecified, standing/m^3	Raw	mm^3	0.18	0.29	0.26	0.34
630	Wood, soft, standing	Raw	cm^3	15.95	64.36	58.27	76.35
631	Wood, primary forest, standing	Raw	mm^3	291.74	30.45	27.57	36.13
632	Wood, hard, standing	Raw	cm^3	4.30	43.82	42.47	46.46
633	Water, well, in ground	Raw	cu.in	52.73	511.40	494.06	545.53
634	Water, unspecified	Raw	dm^3	8.43	51.61	46.78	61.14

	natural origin/m^3						
635	Water, turbine use, unspecified natural origin	Raw	m^3	12.45	25.26	22.88	29.94
636	Water, salt, sole	Raw	cu.in	8.59	207.46	187.77	246.21
637	Water, salt, ocean	Raw	cu.in	310.84	168.45	152.53	199.80
638	Water, river	Raw	dm^3	928.29	21.70	20.24	24.59
639	Water, lake	Raw	cm^3	57.39	371.99	353.46	408.48
640	Water, cooling, unspecified natural origin/m^3	Raw	dm^3	19.47	177.52	172.55	187.32
641	Volume occupied, underground deposit	Raw	mm^3	195.13	205.40	186.16	243.30
642	Volume occupied, reservoir	Raw	^{m3}day	5.73	19.84	17.97	23.53
643	Volume occupied, final repository for radioactive waste	Raw	mm^3	1.88	13.54	12.26	16.06
644	Volume occupied, final repository for low-active radioactive waste	Raw	mm^3	7.52	58.33	52.82	69.18
645	Vermiculite, in ground	Raw	µg	54.78	357.88	339.85	393.36
646	Uranium, in ground	Raw	mg	3.71	28.40	25.71	33.68
647	Uranium oxide, 332 GJ per kg, in ore	Raw	mg	93.66	141.42	127.95	167.93
648	Ulexite, in ground	Raw	µg	71.60	264.90	240.00	313.92
649	Transformation, to water courses, artificial	Raw	mm^2	16.46	44.74	40.53	53.04
650	Transformation, to water bodies, artificial	Raw	mm^2	16.68	158.66	143.78	187.96
651	Transformation, to urban, discontinuously built	Raw	mm^2	0.03	0.03	0.03	0.04
652	Transformation, to unknown	Raw	mm^2	2.63	13.20	11.98	15.60
653	Transformation, to traffic area, road	Raw	mm^2	35.67	196.35	183.28	222.07

	network						
654	Transformation, to traffic area, road embankment	Raw	mm^2	2.90	23.28	22.07	25.64
655	Transformation, to traffic area, rail network	Raw	mm^2	0.47	401.57	363.33	476.85
656	Transformation, to traffic area, rail embankment	Raw	mm^2	0.43	365.32	330.54	433.81
657	Transformation, to shrub land, sclerophyllous	Raw	mm^2	51.74	145.63	137.74	161.16
658	Transformation, to sea and ocean	Raw	mm^2	8.84	0.01	0.01	0.01
659	Transformation, to permanent crop, fruit, intensive	Raw	mm^2	16.16	1.63	1.47	1.93
660	Transformation, to pasture and meadow	Raw	mm^2	31.03	1.26	1.14	1.49
661	Transformation, to mineral extraction site	Raw	cm^2	14.24	59.99	54.32	71.14
662	Transformation, to industrial area, vegetation	Raw	mm^2	18.07	90.41	83.96	103.11
663	Transformation, to industrial area, built up	Raw	mm^2	51.39	64.96	58.92	76.85
664	Transformation, to industrial area, benthos	Raw	mm^2	17.74	0.69	0.63	0.82
665	Transformation, to industrial area	Raw	mm^2	119.03	231.29	225.13	243.41
666	Transformation, to heterogeneous, agricultural	Raw	cm^2	13.40	2.57	2.33	3.05
667	Transformation, to forest, intensive, short-cycle	Raw	mm^2	28.18	2.94	2.66	3.49
668	Transformation, to	Raw	cm^2	2.54	22.19	21.11	24.31

	forest, intensive, normal						
669	Transformation, to forest, intensive, clear-cutting	Raw	mm^2	28.18	2.94	2.66	3.49
670	Transformation, to forest, intensive	Raw	mm^2	16.24	8.49	7.72	10.01
671	Transformation, to forest	Raw	mm^2	67.58	204.03	190.82	230.05
672	Transformation, to dump site, slag compartment	Raw	mm^2	0.04	0.06	0.05	0.07
673	Transformation, to dump site, sanitary landfill	Raw	mm^2	0.30	0.24	0.22	0.28
674	Transformation, to dump site, residual material landfill	Raw	mm^2	11.89	79.22	77.31	82.97
675	Transformation, to dump site, inert material landfill	Raw	mm^2	39.50	66.11	60.15	77.84
676	Transformation, to dump site, benthos	Raw	cm^2	16.63	16.24	14.70	19.28
677	Transformation, to dump site	Raw	mm^2	297.03	330.79	326.55	339.14
678	Transformation, to arable, non-irrigated, fallow	Raw	mm^2	0.41	2.92	2.65	3.46
679	Transformation, to arable, non-irrigated	Raw	cm^2	3.39	33.92	30.76	40.15
680	Transformation, to arable	Raw	mm^2	9.18	37.69	34.17	44.64
681	Transformation, from unknown	Raw	cm^2	5.78	24.92	23.05	28.60
682	Transformation, from tropical rain forest	Raw	mm^2	28.18	2.94	2.66	3.49
683	Transformation, from shrub land,	Raw	mm^2	59.41	161.02	151.68	179.41

	sclerophyllous						
684	Transformation, from sea and ocean	Raw	cm²	16.81	16.25	14.71	19.29
685	Transformation, from pasture and meadow, intensive	Raw	mm²	0.28	2.77	2.51	3.27
686	Transformation, from pasture and meadow	Raw	mm²	124.85	253.05	238.54	281.62
687	Transformation, from mineral extraction site	Raw	mm²	23.69	92.23	83.76	108.91
688	Transformation, from industrial area, vegetation	Raw	mm²	0.07	0.04	0.03	0.04
689	Transformation, from industrial area, built up	Raw	mm²	0.04	0.02	0.02	0.03
690	Transformation, from industrial area, benthos	Raw	mm²	8.84	0.01	0.01	0.01
691	Transformation, from industrial area	Raw	mm²	31.13	5.70	5.16	6.76
692	Transformation, from forest, intensive, clear-cutting	Raw	mm²	28.18	2.94	2.66	3.49
693	Transformation, from forest, extensive	Raw	cm²	2.89	22.52	21.42	24.69
694	Transformation, from forest	Raw	cm²	26.63	55.26	50.02	65.58
695	Transformation, from dump site, slag compartment	Raw	mm²	0.04	0.06	0.05	0.07
696	Transformation, from dump site, sanitary landfill	Raw	mm²	0.30	0.24	0.22	0.28
697	Transformation, from dump site, residual material landfill	Raw	mm²	11.89	79.22	77.31	82.97
698	Transformation, from dump site, inert material	Raw	mm²	39.50	66.11	60.15	77.84

	landfill						
699	Transformation, from arable, non-irrigated, fallow	Raw	mm^2	0.23	1.87	1.70	2.22
700	Transformation, from arable, non-irrigated	Raw	cm^2	3.39	33.89	30.73	40.12
701	Transformation, from arable	Raw	mm^2	0.94	7.03	6.37	8.34
702	TiO2, 95% in rutile, 0.40% in crude ore, in ground	Raw	ng	117.04	524.26	475.03	621.20
703	TiO2, 54% in ilmenite, 2.6% in crude ore, in ground	Raw	g	0.42	1.06	0.96	1.26
704	Tin, 79% in cassiterite, 0.1% in crude ore, in ground	Raw	mg	0.83	3.04	2.75	3.60
705	Tellurium, 0.5ppm in sulfide, Te 0.2ppm, Cu and Ag, in crude ore, in ground	Raw	µg	0.49	1.15	1.04	1.36
706	Tantalum, 81.9% in tantalite, 1.6E-4% in crude ore, in ground	Raw	µg	3.60	8.31	7.53	9.84
707	Talc, in ground	Raw	mg	10.62	1.69	1.55	1.94
708	Sylvite, 25 % in sylvinite, in ground	Raw	mg	34.25	12.27	11.13	14.53
709	Sulfur, in ground	Raw	mg	4.67	1.64	1.49	1.94
710	Stibnite, in ground	Raw	ng	2.98	32.84	29.75	38.92
711	Sodium sulphate, various forms, in ground	Raw	mg	221.22	104.19	94.34	123.58
712	Sodium nitrate, in ground	Raw	ng	30.48	3.03	2.77	3.56
713	Sodium chloride, in ground	Raw	g	9.87	9.29	8.45	10.96
714	Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu	Raw	µg	0.45	1.04	0.94	1.23

	0.38%, Pb 0.014%, in ore, in ground						
715	Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore, in ground	Raw	µg	0.68	1.58	1.43	1.87
716	Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore, in ground	Raw	µg	0.69	1.61	1.46	1.91
717	Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore, in ground	Raw	ng	302.75	705.69	639.69	835.62
718	Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te, in crude ore, in ground	Raw	µg	3.28	7.65	6.94	9.06
719	Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In, in ground	Raw	µg	4.60	10.71	9.71	12.69
720	Shale, in ground	Raw	µg	104.33	118.45	107.68	139.65
721	Sand, unspecified, in ground	Raw	mg	3.21	3.72	3.37	4.40
722	Rhenium, in crude ore, in ground	Raw	ng	5.72	173.03	156.62	205.34
723	Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Raw	ng	14.50	391.53	354.37	464.68
724	Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Raw	ng	4.63	125.01	113.14	148.36
725	Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Raw	ng	31.27	527.54	477.51	626.02
726	Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in	Raw	ng	8.72	147.16	133.20	174.63

	ore, in ground						
727	Phosphorus, 18% in apatite, 4% in crude ore, in ground	Raw	mg	108.91	64.84	58.73	76.88
728	Phosphorus, 18% in apatite, 12% in crude ore, in ground	Raw	mg	49.17	32.41	29.36	38.42
729	Peat, in ground	Raw	mg	66.05	15.85	14.45	18.62
730	Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Raw	µg	0.52	13.02	11.79	15.45
731	Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Raw	µg	0.22	5.42	4.90	6.43
732	Olivine, in ground	Raw	µg	14.09	16.38	14.91	19.29
733	Oil, crude, in ground	Raw	kg	3.48	6.41	5.80	7.61
734	Occupation, water courses, artificial	Raw	cm^2a	13.76	41.44	37.54	49.11
735	Occupation, water bodies, artificial	Raw	cm^2a	9.29	48.59	44.06	57.51
736	Occupation, urban, discontinuously built	Raw	mm^2a	1.40	1.70	1.55	2.02
737	Occupation, traffic area, road network	Raw	cm^2a	14.80	139.94	130.00	159.51
738	Occupation, traffic area, road embankment	Raw	cm^2a	4.12	35.56	33.70	39.23
739	Occupation, traffic area, rail network	Raw	m^2a	0.00	0.17	0.16	0.21
740	Occupation, traffic area, rail embankment	Raw	m^2a	0.00	0.16	0.14	0.19
741	Occupation, shrub land, sclerophyllous	Raw	mm^2a	258.79	728.77	689.30	806.47
742	Occupation, permanent crop, fruit, intensive	Raw	cm^2a	11.48	1.16	1.05	1.37
743	Occupation, mineral	Raw	cm^2a	19.96	116.78	108.16	133.76

	extraction site						
744	Occupation, industrial area, vegetation	Raw	cm^2a	8.63	40.75	37.71	46.74
745	Occupation, industrial area, built up	Raw	cm^2a	29.14	30.78	27.92	36.41
746	Occupation, industrial area, benthos	Raw	mm^2a	878.85	12.60	11.40	14.95
747	Occupation, industrial area	Raw	cm^2a	50.00	194.60	179.75	223.84
748	Occupation, forest, intensive, short-cycle	Raw	mm^2a	788.90	82.35	74.55	97.70
749	Occupation, forest, intensive, normal	Raw	m^2a	0.03	0.31	0.29	0.33
750	Occupation, forest, intensive	Raw	cm^2a	24.38	12.74	11.59	15.02
751	Occupation, dump site, benthos	Raw	cm^2a	16.63	16.24	14.70	19.28
752	Occupation, dump site	Raw	cm^2a	392.70	428.39	422.03	440.91
753	Occupation, construction site	Raw	cm^2a	24.63	11.23	10.58	12.53
754	Occupation, arable, non-irrigated	Raw	cm^2a	1.84	18.34	16.63	21.71
755	Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	Raw	g	7.32	21.97	19.92	26.00
756	Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	Raw	mg	1.60	1.35	1.23	1.60
757	Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	Raw	mg	1.58	106.04	96.02	125.78
758	Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	Raw	g	1.17	0.01	0.01	0.02
759	Molybdenum, 0.022% in	Raw	mg	0.78	52.54	47.57	62.32

	sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground						
760	Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	Raw	mg	1.01	4.04	3.69	4.74
761	Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	Raw	mg	7.11	28.36	25.89	33.23
762	Metamorphous rock, graphite containing, in ground	Raw	mg	3.15	22.13	20.05	26.23
763	Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	Raw	g	0.07	4.83	4.37	5.73
764	Magnesium, 0.13% in water	Raw	µg	5.55	33.16	30.49	38.41
765	Magnesite, 60% in crude ore, in ground	Raw	g	3.31	11.05	10.03	13.07
766	Lithium, 0.15% in brine, in ground	Raw	ng	87.92	28.47	26.03	33.27
767	Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in ground	Raw	mg	105.40	86.06	77.94	102.03
768	Kieserite, 25% in crude ore, in ground	Raw	µg	237.11	113.88	103.79	133.76
769	Kaolinite, 24% in crude ore, in ground	Raw	mg	95.91	17.77	16.35	20.57
770	Iron, 46% in ore, 25% in crude ore, in ground	Raw	g	254.53	737.10	668.99	871.20
771	Iodine, 0.03% in water	Raw	µg	8.17	2.70	2.46	3.18
772	Indium, 0.005% in sulfide, In 0.003%, Pb, Zn, Ag, Cd, in ground	Raw	µg	2.01	15.91	14.41	18.85

773	Gypsum, in ground	Raw	µg	356.42	437.56	396.53	518.34
774	Gravel, in ground	Raw	kg	1.81	21.96	19.89	26.02
775	Granite, in ground	Raw	ng	7.29	6.39	5.80	7.55
776	Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	Raw	ng	41.87	91.85	83.26	108.74
777	Gold, Au 7.1E-4%, in ore, in ground	Raw	µg	0.70	1.53	1.39	1.81
778	Gold, Au 6.7E-4%, in ore, in ground	Raw	µg	0.62	1.36	1.23	1.61
779	Gold, Au 4.9E-5%, in ore, in ground	Raw	µg	0.40	0.88	0.80	1.04
780	Gold, Au 4.3E-4%, in ore, in ground	Raw	ng	167.11	366.56	332.31	433.99
781	Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore, in ground	Raw	µg	0.67	1.48	1.34	1.75
782	Gold, Au 1.4E-4%, in ore, in ground	Raw	µg	0.44	0.97	0.88	1.15
783	Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore, in ground	Raw	ng	368.68	808.78	733.21	957.55
784	Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore, in ground	Raw	ng	201.05	441.04	399.83	522.17
785	Gas, natural, in ground	Raw	m^3	7.49	1.67	1.51	1.98
786	Gas, mine, off-gas, process, coal mining/m^3	Raw	dm^3	2.44	32.38	31.62	33.88
787	Gallium, 0.014% in bauxite, in ground	Raw	ng	1.48	9.01	8.16	10.69
788	Fluorspar, 92%, in ground	Raw	mg	764.77	422.10	382.21	500.63
789	Fluorine, 4.5% in apatite, 3% in crude ore, in ground	Raw	mg	12.23	8.08	7.32	9.58
790	Fluorine, 4.5% in	Raw	mg	27.23	16.21	14.68	19.22

	apatite, 1% in crude ore, in ground						
791	Feldspar, in ground	Raw	µg	0.31	2.03	1.84	2.40
792	Energy, solar, converted	Raw	kJ	0.52	3.25	2.94	3.85
793	Energy, potential (in hydropower reservoir), converted	Raw	MJ	1.41	3.26	2.95	3.87
794	Energy, kinetic (in wind), converted	Raw	kJ	38.37	143.09	129.64	169.57
795	Energy, gross calorific value, in biomass, primary forest	Raw	kJ	3.14	0.33	0.30	0.39
796	Energy, gross calorific value, in biomass	Raw	Wh	65.93	324.87	304.17	365.62
797	Dolomite, in ground	Raw	g	0.64	1.82	1.66	2.15
798	Diatomite, in ground	Raw	ng	28.70	315.98	286.25	374.52
799	Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	Raw	g	0.38	1.53	1.39	1.79
800	Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	Raw	mg	77.09	307.72	280.90	360.53
801	Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	Raw	g	91.93	1.16	1.06	1.36
802	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	Raw	g	22.45	0.21	0.19	0.25
803	Colemanite, in ground	Raw	mg	5.11	2.21	2.01	2.62
804	Cobalt, in ground	Raw	µg	2.86	113.18	102.43	134.34
805	Coal, hard, unspecified, in ground	Raw	oz	8.90	110.52	107.81	115.85
806	Coal, brown, in ground	Raw	g	85.24	360.24	326.37	426.92

807	Coal, 26.4 MJ per kg, in ground	Raw	kg	368.31	422.52	382.28	501.75
808	Clay, unspecified, in ground	Raw	g	42.09	246.64	223.67	291.87
809	Clay, bentonite, in ground	Raw	g	3.57	10.39	9.43	12.29
810	Cinnabar, in ground	Raw	µg	13.92	13.94	12.70	16.37
811	Chrysotile, in ground	Raw	µg	145.89	159.71	145.50	187.69
812	Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	Raw	g	2.29	7.26	6.58	8.60
813	Carbon, in organic matter, in soil	Raw	mg	45.36	4.74	4.29	5.62
814	Carbon dioxide, in air	Raw	g	196.51	376.95	344.42	441.00
815	Calcite, in ground	Raw	oz	5.34	29.85	27.07	35.31
816	Cadmium, 0.30% in sulfide, Cd 0.18%, Pb, Zn, Ag, In, in ground	Raw	mg	0.12	0.93	0.84	1.10
817	Bromine, 0.0023% in water	Raw	µg	28.47	10.97	9.99	12.90
818	Borax, in ground	Raw	µg	9.08	66.72	61.07	77.83
819	Basalt, in ground	Raw	g	0.22	1.39	1.28	1.61
820	Barite, 15% in crude ore, in ground	Raw	g	7.63	21.84	19.77	25.92
821	Anhydrite, in ground	Raw	µg	36.85	41.84	38.03	49.32
822	Aluminium, 24% in bauxite, 11% in crude ore, in ground	Raw	g	1.92	15.42	13.97	18.28