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Underground Coal Gasification:

Overview of an Economic and Environmental Evaluation.

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Underground Coal Gasification:

Overview of an Economic and Environmental Evaluation.

by

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Report

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Dedication

Dedicated to my father, Honorable: Elijah John Herbert Kitaka-Gawera former M.P., F.C.I.S, M.B.I.M., whose unwavering belief in the idea of higher learning was an inspiration and encouragement to return for my advanced education. May the Lord bless him for all he has provided to me in life.

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The University of Texas at Austin, 2011

Supervisor: Thomas Edgar.

Abstract

This paper examines an overview of the economic and environmental aspects of Underground Coal Gasification (UCG) as a viable option to the above ground Surface Coal Gasification (SCG). In addition, some highlights, hurdles and opportunities from early investment to successful commercial application of some worldwide UCG projects will be discussed. Global energy demands have prompted continual crude oil consumption at an astronomical pace. As such, the most advanced economies are looking for local and bountiful resources to challenge crude oil's dependence for which coal provides the best alternative so far. In the U.S, the Department of Energy (DOE), the National Energy Transportation Laboratory (NETL) along with the Lawrence Livermore National Laboratory (LLNL) continue to support pilot programs that develop improved methods for clean coal technologies to produce coal derived fuels competitive with crude oil fuels at about $30 per barrel [1].Lignite, the softest of the four types of coal, is the best candidate for underground coal gasification due to its abundance, high volatility and water to carbon content in its rock formation. The biggest challenge of modern humans is to find a balance of energy consumption, availability of resources, production costs and environmental conservation. Additionally, UCG has environmental benefits that include mitigating CO_2 emissions through Carbon Capture and Storage (CCS) and reduced overall surface pollutants, making it the preferred choice over SCG.

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Introduction

Underground Coal gasification (UCG) is an *in-situ* gasification process carried out in shut down deep coal mines or inaccessible coal seams at depths preferably more than 200 meters. The product gas called Synthetic gas or 'syngas' is produced by injecting an oxidant and bringing this gas to the surface using outlet production wells. Coal, available in variable carbon and moisture content, is the most abundant fuel resource in industrialized economies like the United States (US), European Union (EU), Russia, India and China, also the largest consumers of crude oil. The idea of clean coal fuels, has received a lot of attention for the purposes of increasing coal usage as a secure energy resource while addressing environmental mitigation.

Amongst the main types of coal are Lignite, Sub- bituminous, Bituminous and Anthracite based on their carbon-to-hydrogen and moisture content. Lignite coal is a very abundant type of coal in the U.S especially in North Dakota, Wyoming, Texas and the coastal areas. The wider implications for the product syngas gas are such that it can be utilized as a feed stock to chemical manufacturing and most importantly for the electrical and transportation infrastructures. The flexible use of syngas products can mitigate rising crude oil prices while addressing the need to decouple from foreign oil as part of a comprehensive energy policy.

Underground gasification is useful in utilizing the vast resources of lignite coal deep beneath the surface that are technically complicated to mine by traditional methods. The global production of electricity using coal now accounts for over 40% of total fuel usage but produces at least 60 % of total CO_2 emissions. The dry ash from above surface combustion presents additional environmental challenges, some of which will be addressed in this paper. UCG has the potential to significantly reduce both CO_2, a green house gas (GHG), and dry ash particulates to the atmosphere. Although UCG is a technology with relatively little wide scale adoption, it's destined to provide an important element in an era in which coal, with greater known reserves will rival the dominance of oil in the global energy and transportation sectors. Coal's high CO_2 emission rates are attributed to its low carbon to hydrogen ratio~1:1 thus emitting the highest rates of CO_2 per KWh of power produced. Underground gasification can be used to decarbonize coal through steam gasification, methanation, hydrogenation and conversion to liquid fuels, at relatively low economic and environmental costs compared to surface gasification.

UCG is a gateway to low and medium fuels by means of Gas-to-Liquid (GTL) or Coal-to-Liquids (CTL) fuels using methods like the Fisher-Tropsch or Bergius process. Additionally, UCG can be combined with other existing technologies like Integrated Gasification and Combined Cycle (IGCC) to provide power generation at minimal emissions and capital costs. There are efforts to include emerging pollution control technologies like carbon capture and storage for CO_2 in the deep cavities vacated by gasified coal.

Furthermore, the paper will provide highlights of the use of underground gasification process and its development as a source of production syngas and natural gas. Both these gases can be converted to fuels with minimum penalty to the environment and overall capital investment. Finally, this dissertation will provide an economic and environmental justification through highlights, hurdles and opportunities over existing technologies like surface coal mining.

History and Background

Underground coal gasification has been debated and examined for over 150 years. The earliest recorded mention of this technology was back in 1868, to the Chemical Society of London by Sir Williams Siemens, who suggested underground gasification of waste and slack in coal mines. A Russian chemist, Dmitri Mendelevev, further developed Siemens' idea over the subsequent decades, with notable experimental work on UCG done by the likes of distinguished Victorian scientist and Nobel Prize winner, Sir William Ramsay.

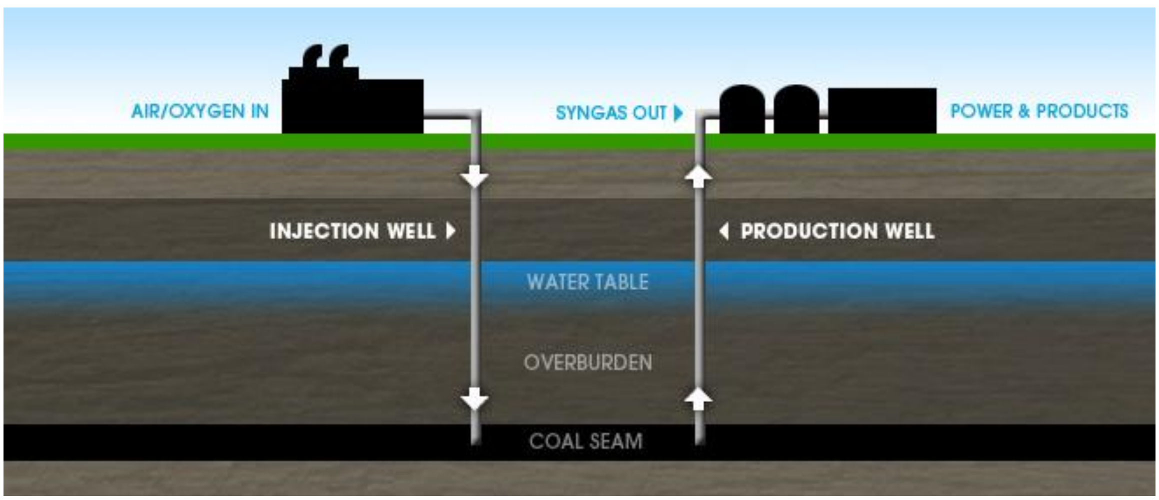
Initial tests done in the early part of the century for this technology carried out by a Russian state owned organization- Podzemgaz, were a failure. The first successful test was completed around 1934 in the Donetsk Basin. The former Soviet Union (FSU) is credited with most of the early pilot and industrial scale implementation including a facility in present-day Uzbekistan that has been in operation since 1961. Interest in UCG increased after the Second World War spawning pilot projects across Europe, specifically during the 1950's at the Newman Spinney facility in the United Kingdom [2]. But the abundance of natural gas and falling oil prices caused most of these projects to be abandoned in the 1960s. The early 1970s reversed the trend of falling oil prices with a global oil embargo from Arab nations, resulting in renewed interest in UCG research and other alternative energy resources. As such, there are several field tests in Europe under the European working group, Australia, New Zealand, South Africa, Canada, China, India and the United States to mention just a few.

Amongst the numerous companies utilizing this technology are Linc Energy, Ergo Exergy Technologies and the Lawrence Livermore National Laboratory which have emerged as premiere authorities directing some of the largest global UCG projects. In the U.S, there have been over 30 UCG pilot projects, of which some of earlier projects by the DOE were conducted in Wyoming at Hoe Creek, Rocky Mountain and Hanna from 1976 to 1995 [24]. Notable was the ten year Chinchilla test project by Linc Energy in Australia. From about 1997 to 2009, more than 35,000 tons of coal was gasified at Chinchilla validating the viability of UCG as an economic and environmentally practical energy resource. Currently, China is spearheading an aggressive program implementing massive investments in UCG research and commercialization with the largest known operational plants.

Methods

The term UCG prescribes to the process where coal gasification is done underground. In this case, the underground cavity acts as the reactor for partial combustion to produce a combination of carbon monoxide, hydrogen and a lesser content of carbon dioxide gas mixture referred to as 'Synthetic Gas'- or syngas. Air or oxygen is injected into one well and a controlled combustion reaction is started in the seam itself – different from a natural coal seam fire. Gases are collected through the second well and are separated in a facility at the surface.

Figure 1: Showing the basic Underground Coal Gasification concept [11].



Hydrogen is the primary energy-containing gas in the mix which can be liquefied by already proven state-of-the art technologies or with a combination of carbon monoxide be combusted directly to produce heat. Although CO_2 is one of the products of UCG, it's a product with an economic potential for use in enhanced oil recovery. As a by-product, CO_2 can be stored in void spaces of combusted cavities using emerging Carbon Capture and Storage (CCS) technologies.

There are two different methods of UCG that have evolved and are commercially available:

- One method uses vertical wells for opening the pathway between the wells and reverse combustion to open up internal pathways in the coal. This process was used in the Soviet Union and later tested in Chinchilla, Australia. The early work in Russia focused on exploiting shallow and often thin coal seams that were relatively easy to drill into but would not be considered economically or environmentally suitable today. The shallow seams resulted in both low pressure in the reactor and low quality gas, compared to deeper systems. In addition, there was difficulty in creating a physical connection between the vertical wells, which accounted for the high failure rate of early UCG work. Shallow seams are not suitable for gasification because of high gas losses, potential breakthrough to surface due to fracturing and possible contamination of ground waters. Thin seams, less than 2m thick, are difficult to exploit economically unless one has a multi-seam environment [3].

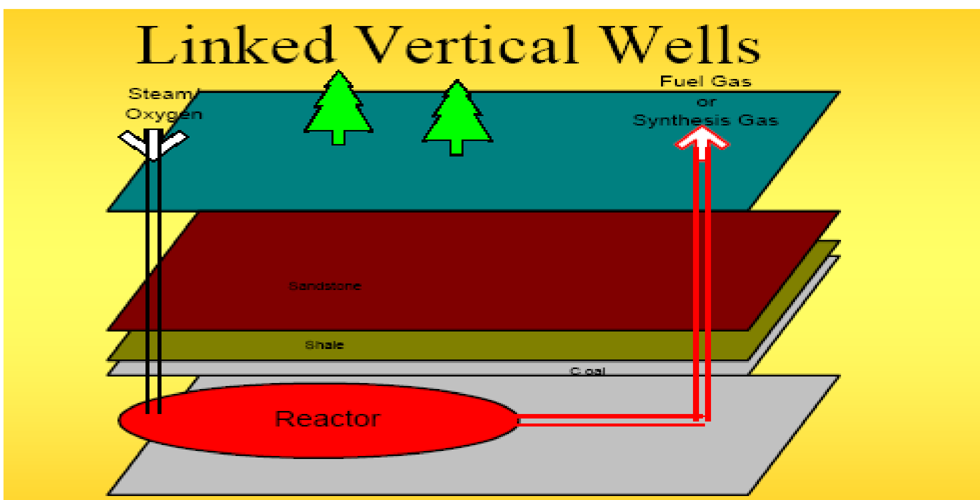


Figure 2. Showing a basic schematic of Linked Vertical Wells [4].

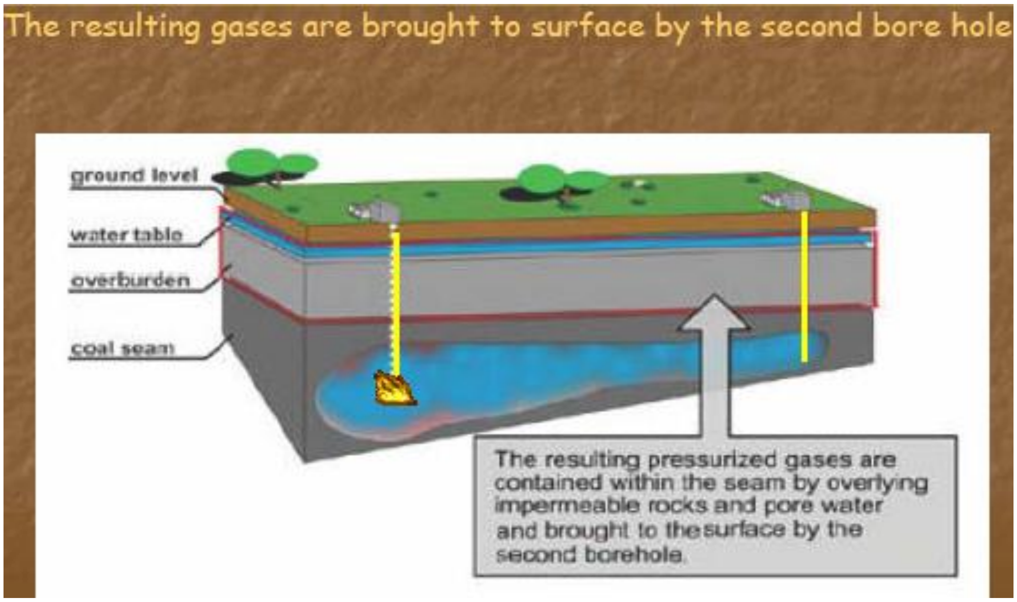


Figure 3. Schematic of Boreholes in Vertical wells [4].

- The second method was largely developed from 1974 – 1985 by researchers at the Lawrence Livermore Laboratory in the U.S. and used in European trials. Dedicated inseam boreholes are created using drilling and completion technology adapted from oil and gas production. It has a moveable injection point known as a Controlled Retraction Injection Point (CRIP) and generally uses oxygen or enriched air for gasification. The CRIP concept has lead to the highest gasification efficiency in terms of oxygen usage and will minimize the occurrence of subsidence or possibly eliminate it, by using wider barrier pillars between panels. The use of inseam boreholes can be used to mine deeper coal seams to depths over 3,000 ft providing higher pressure and better quality gas. Environmentally, this method has other benefits that make it an attractive option. Coal seams at depths deep beyond 600 ft bypass most water basins usually located at less than 200 ft which significantly reduces the threat of water contamination. Additionally, at depths beyond 3,000 ft, CO_2 can be stored in a critical state more effectively and abundantly in the evacuated cavities. The CRIP method has also employed techniques similar to 'Hydraulic fracturing' or Hydro-fracking in combination with reverse combustion linking injection and production wells [5].

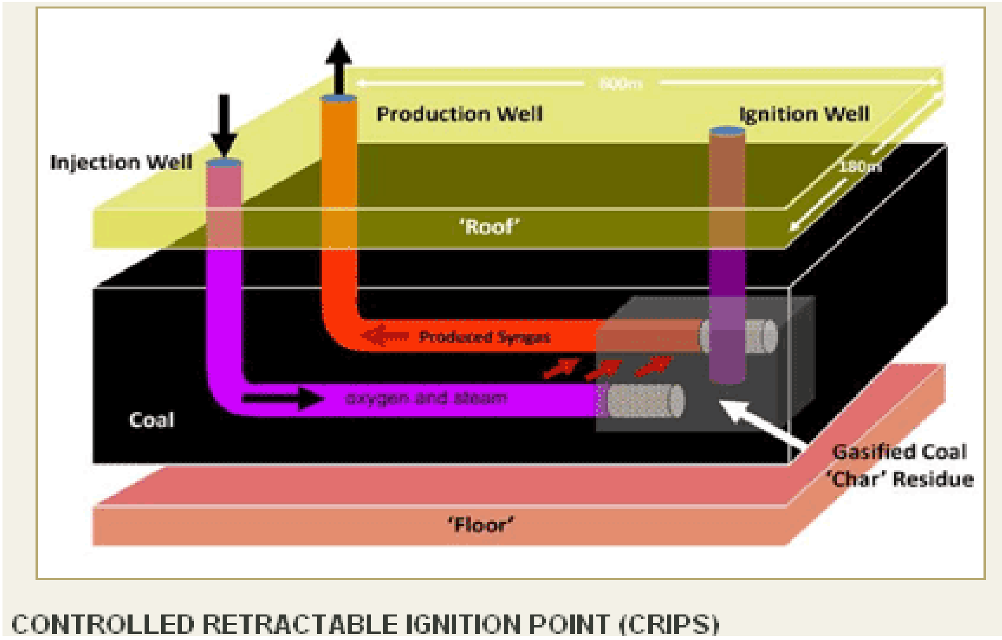


Figure 4: Showing schematic of Controlled Retractable Ignition Point (CRIP).

UCG product syngas can be burned for electrical power generation or transportation through the production of liquid fuels using Gas-to-Liquids (GTL) or Fuel cell technology. Syngas can be processed further to remove sulfur through a Flue gas desulphurization (FGD) unit, after which it can be synthesized into low emission fuels that provide for better engine performance and improved emissions.

Gas-to-Liquid processes are classified into two methods: (i) Direct conversion to liquids and (ii) Indirect conversion to liquids processes.

- **Direct or Hydrogenation Process.**

The direct conversion of methane from the methanation process, (typically 85 to 90 per cent of natural gas), eliminates the cost of producing synthesis gas but involves a high activation energy and is difficult to control. Several direct conversion processes have been developed but none have been commercialized because they are economically unattractive. Another method of direct conversion of GTL, is by hydrogenation process using the Bergius process. The reaction occurs between 400 °C (752 °F) to 1,500 °C (2,732 °F) and 20 to 70 MPa hydrogen pressure. This method has also been found to be much more expensive than the indirect conversion process.

- **Indirect conversion processes**

The main indirect conversion process is the Fischer-Tropsch process. In this process, gasified coal creates the syngas (a balanced purified mixture of CO and H_2 gas). Next, Fischer-Tropsch catalysts, Iron and Cobalt are used to convert the syngas into light hydrocarbons, which are further processed into low sulfur gasoline or diesel fuels.

Fischer–Tropsch process

The **Fischer–Tropsch** technology converts coal-gas and other low-value refinery products into high-value, clean-burning fuels. The resultant fuel is colorless with low toxicity. In the case of gasification, Fischer–Tropsch synthesis chemical reactions convert a mixture of carbon monoxide and hydrogen into liquid hydrocarbons. The process is a key component of the Gas-to-Liquids technology in the production of synthetic fuels like ultra-low sulfur diesel, synthetic lubricants and fuel additives that are typically less polluting than crude oil derivatives.

Process chemistry

Gasification converts solid coal fuel into gaseous reactants, i.e. CO_2, CO, H_2. A gasifier converts hydrocarbon feedstock into gaseous components by applying heat under pressure in the presence of steam. The amount of air or oxygen available inside the gasifier is carefully controlled so that only a relatively small portion of the fuel burns completely. The synthetic gas obtained tends to vary H_2/CO ratio from ~0.7 for Low BTU to the ideal ratio of ~2 for medium BTU gas. Syngas can also be converted into methanol, which can be used as a fuel, or fuel additive. Another product of syngas, H_2 can be used for fuel cells, the production of Ammonia based fertilizers or for power generation using new General Electric high temperature H_2 steam turbines. The mixture of O_2 in the oxidant determines the quality of H_2 to CO in the syngas. Conversely, if air is used as the oxidant, the product gas will have an approximate proportion of N_2 gas in the syngas making it the preferred feed stock for the production of Ammonia based fertilizers.

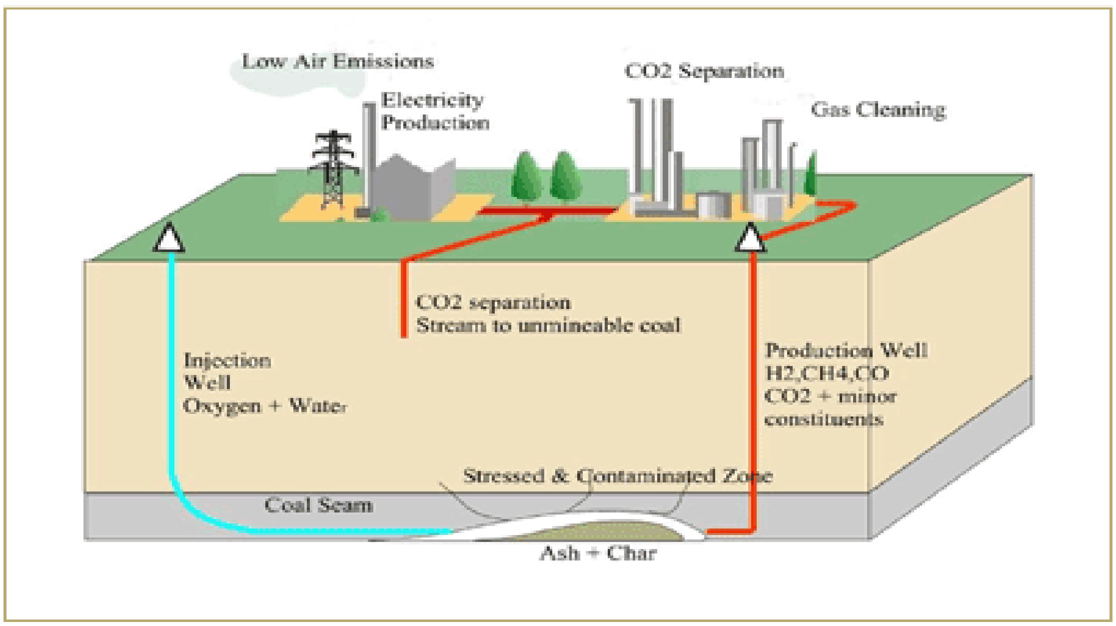


Figure 5: Showing general UCG process, IGCC and pollution control.

Syngas can also be converted to liquids through conversion to methanol which is subsequently polymerized into alkanes over a zeolite catalyst. This process is called Mobil

MTG Process and was developed by Mobil in early 1970s. The preferred reactions for fuels should give long chain alkanes which usually are in liquid form with a high energy density and can be easily transported. The general equation is shown below:

$$(2n+1)\ H_2 + n\ CO \rightarrow C_nH_{(2n+2)} + n\ H_2O$$

Most alkanes produced tend to be straight-chain alkanes, although some branched alkanes can also be formed. Additionally, competing reactions result in the formation of alkenes, as well as alcohols and other oxygenated hydrocarbons.

Gasification occurs primarily via the water-gas shift reaction, which is a dirty, expensive (endergonic) and an energy intensive process.

- water gas shift reaction provides a source of hydrogen:

$$2C(s) + O_2(g) + H_2O(g) -> CO(g) + CO_2(g) + H_2(g)$$

Other competing reactions are possible as a result of gasification with other major reactions employed to adjust the H_2/CO ratio:

$$C + CO_2(g) -> 2CO(g)$$

$$2H_2O(g) + 2CO(g) -> 4H_{2(g)} + 2CO_{2(g)}$$

- Steam reforming is another important reaction, which can be used to convert methane into CO and H_2:
  $CH_4 + H_2O \rightarrow CO + 3\ H_2$
- Methanation reactions are used to produce industrial feed stock, electrical gas or ethanol fuel:
  $2CO(g) + 2H_2(g) -> CH_4(g) + CO_2(g)$
  $CO(g) + 2H_2(g) -> CH_3\text{-}OH(g)$

- Desulfurization reactions are used to remove H2S content from gasified Coal:
  $H_2S(g) + O_2(g) -> H_2O(g) + SO_2(g)$

$SO_2(g) + H_2O(g) + 1/2O_2(g)$ - > $H_2SO_4(g)$ (In a wet scrubber)

$H_2SO_4(g)$ + $Ca(OH)_2(l)$ - > $CaSO_4.2H_2O(s)$. In an FGD Unit, removal of H_2S in a wet scrubber to produce gypsum represents one of the many ways in 'gas sweetening.'

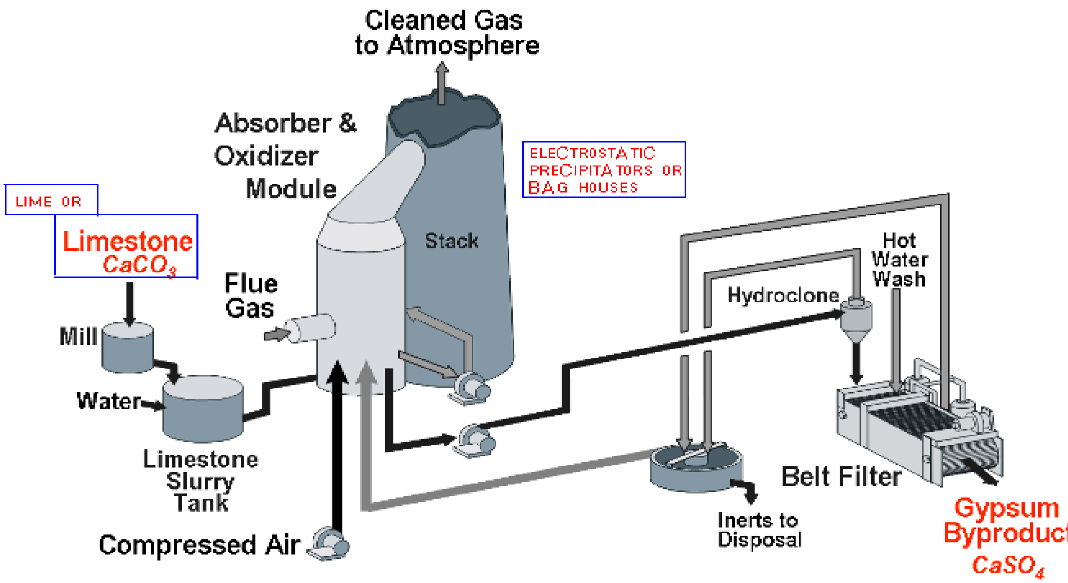


Figure 6. Flue Gas Desulfurization (FGD) unit.

The product of the FGD unit, Gypsum ($CaSO_4.2H_2O$), has a commercial value in the building and construction industry.

Possible chemical mechanisms and kinetics. The conversion of CO to alkanes involves net hydrogenation of CO, the hydrogenolysis of C-O bonds, and the formation of C-C bonds. Such reactions are assumed to proceed via initial formation of surface-bound metal carbonyls. The CO ligand is speculated to undergo dissociation, possibly into oxide and carbide ligands. Other potential intermediates are various C-1 fragments including formyl (CHO), hydroxycarbene (HCOH), hydroxymethyl (CH_2OH), methyl (CH_3), methylene (CH_2), methylidyne (CH), and hydroxymethylidyne (COH). Furthermore and critical to the production of liquid fuels, are reactions that form straight chain C-C bonds, such as migratory insertion. The kinetic order can be determined experimentally through monitoring of intermediates or approximated by computer simulation models.

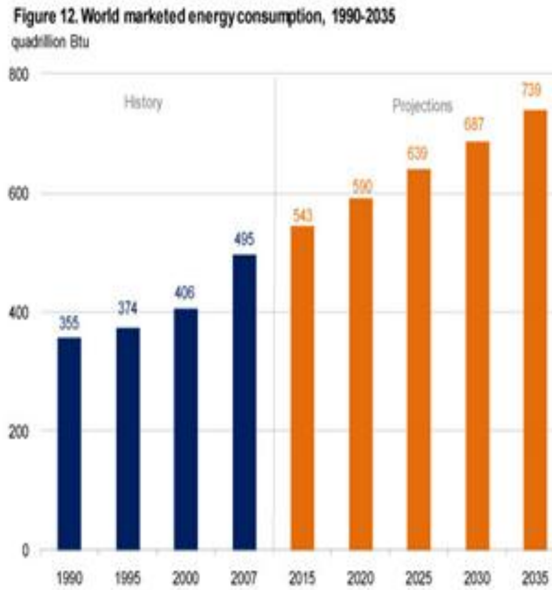
Economics and Commercialization.

In recent years, coal's share in electrical power generation has declined primarily due to competition from cheap natural gas which is responsible for reduced UCG investments in the Soviet Union and Europe. Additionally, because of increased investments in renewable energies like solar and wind, aging coal plants being taken offline, and few new plants being built, the share of coal in U.S power generation has dropped. At its most recent peak in 1988, coal power plants produced 57.0% of U.S power. In 2004, coal's share of electrical production fell below 50% for the first time since 1979 and by 2009, that share dropped to about 45%[9] .However, as indicated by the proceeding figure, projections for global coal reserves exceed those of known crude oil by a margin of 2 to 1, closely followed by reserves of natural gas.

Global Fossil Fuel Reserves	World Petroleum (Billion Barrels)	Natural Gas (Trillion Cubic Feet)	Coal (Billion Short Tons)
World Reserves (Jan 1, 2000)	1,017	5,150	1089*
World Potential Reserve Growth	730	3,660	--
World Undiscovered Potential	939	5,196	--
TOTAL RESERVES	2,686	14,006	1,089
ANNUAL WORLD CONSUMPTION	27.340	84.196	4.740
YEARS OF RESERVES LEFT**	**98**	**166**	**230**
**World Estimated Recoverable Coal*	***Based on current levels of consumption and estimated total reserves*		

Table 1: World Fossil Fuel (Petroleum, Natural Gas, Coal) Assessment[1]

Global energy demand is estimated to rise by an average of about 4% annually. The increase is due to emerging non-OECD economies of the 'BRICS' countries- Brazil, Russia, India, China and South-Africa, the new industrial and manufacturing hubs for global consumers. According to the U.S Energy Information Administration (U.S. E.I.A), total energy consumption in the U.S reduced from about 99.6 quadrillion Btu's in 2006 to 97.8 quadrillion Btu's in 2010 a 1.8% drop possibly due to outsourcing of manufacturing and a housing market bubble that affected global economic activity.



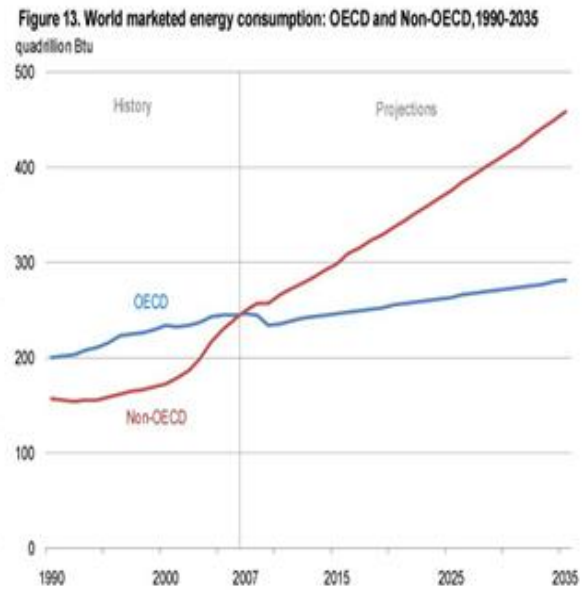


Table 2: Global Energy consumption for Developed (OECD) and Non-OECD countries [9].

The U.S holds over a quarter of the world's known coal reserves. Abundant resources of un-mineable coal in the U.S and other industrial economies make UCG a needed technology. Responsible coal usage to serve the electrical and transportation sectors of any economy significantly relieves the use of crude oil products. For coal plants generating power using Integrated gasification and combined cycle (ICGG) spend a majority of operating costs on coal transportation, manual labor and tunnel maintenance. Additionally, there are significant savings of initial capital due to the absence of surface gasifiers and reduced pollution control equipment which by conservative estimates are at least 10%. For an average investment cost for a 700 MW coal fired plant of about U.S $ 1.5 billion, at least $ 150 million in savings, is realized immediately by applying UCG. For the U.S, being the largest importer and consumer of petroleum crude oil, the savings from utilizing local energy resources will be enormous resulting from reduced capital outflows. For example, a 20% reduction of imported crude oil amounts to over U.S $ 150 billion savings that can be used for local infrastructure development and job creation.

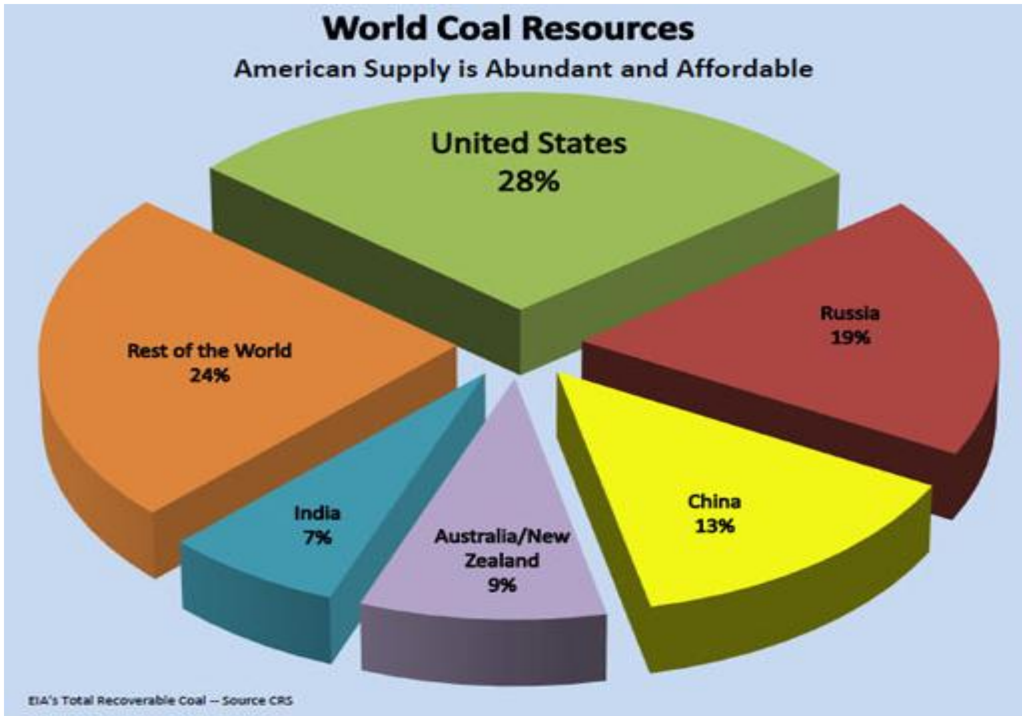


Figure 7: World Coal Reserves.

UCG has shown significant competitive pricing for power production with current technologies. According to a study by Dr. Friedmann et al [14] at the Lawrence Livermore National Laboratory, there are significant savings in every sector from reduced capital and operating plant costs to electrical production $/ KWh. As such, UCG with carbon capture is a very practical alternative for clean coal technology when compared to current surface gasification power generation technologies like IGCC. From this study, it can be deduced that significant savings from power generation and operational expenses can exceed 50% overall, a significant incentive for future investment in the application of UCG. In a separate study by scientists with the Aachen group in Germany, placed the cost of UCG plants with CO_2 storage at equal to or less than surface coal-fired plants without any carbon capture technology. Other estimates have found that UCG syngas can be cheaper than natural gas, even at currently depressed price levels. The proceeding figure from the LLNL study shows some price comparisons of IGCC without CCS and UCG-CCS.

All UCG cases show lower Capex, Opex, making carbon management cheaper

Syngas production
- Total Capital $57.2 M
- Annual OPEX $13.5 M
- Raw syngas $1.62/MMBtu
- Includes15% ROI

UCG-CC power plant
- ~75% surface IGCC capex
- ~55% surface IGCC opex
- Better ROI
- *UCG-CC + CCS ≈ IGCC*

UCG-FT plant
- 10,000 BPD +100 MW
- $622 M Capex
- $53 M Opex
- Diesel @ $63/bbl, naptha @$30/bbl, $62/MW-hr
- 18% ROI

	IGCC	UCG-CC
Megawatts	550	200
Capacity Factor	85	95
Total Capital ($M)	$850	$263
Capital, $/KW	$1544	$1180 *76%*
OPEX, $M/y	$90.1	$20
OPEX, $/MW-hr	$22.0	$12.0 *54%*
Construction	3 years	3 years
Operation	22 years	22 years
Debt/Equity	100%	100%
USFIT rate	35%	35%
Sale price for 15% ROI	$80.6	$51.7
ROR at $62/MW-hr	10.4%	18.3%
Payback at $62/MW-hr	10.8	7.7

Morzenti, 2007
Courtesy GasTech

Lawrence Livermore National Laboratory

9

Table 3: Showing UCG's economic advantages over other technologies [14f].

In terms of capital investment, there are added savings because no miners or surface mining machinery other than drilling equipment is required. Furthermore, without the need for surface reclamation, there is a significant reduction in the environmental penalty and cost. With all these savings, some estimates indicate an overall reduction in plant costs by at least 30% of an equivalent surface coal mine. However, the economic challenge would be in properly assessing the geological quantity of underground coal seams that could sustain UCG to justify the relevant investment albeit the fractional cost to a surface mine. In addition to the quantity of coal within the seam, the quality of the product gas has been found to be proportional to the seam thickness. As such, a thickness of less than 2 m was found to be economically impractical [10].

Lignite coal seems to provide the best economics because it has higher water content, high volatility and permeability. Since lignite rock formations have higher water composition within than other types of coal, less water is injected for steam reforming. High permeability per unit volume within lignite rocks allows for better gas transport between the reactant and production wells. Consequently, lignite coal requires less resources in terms of water and induced pressure when hydro-fracturing or electric-linkage is used for UCG production which reduces the overall investment and capital costs.

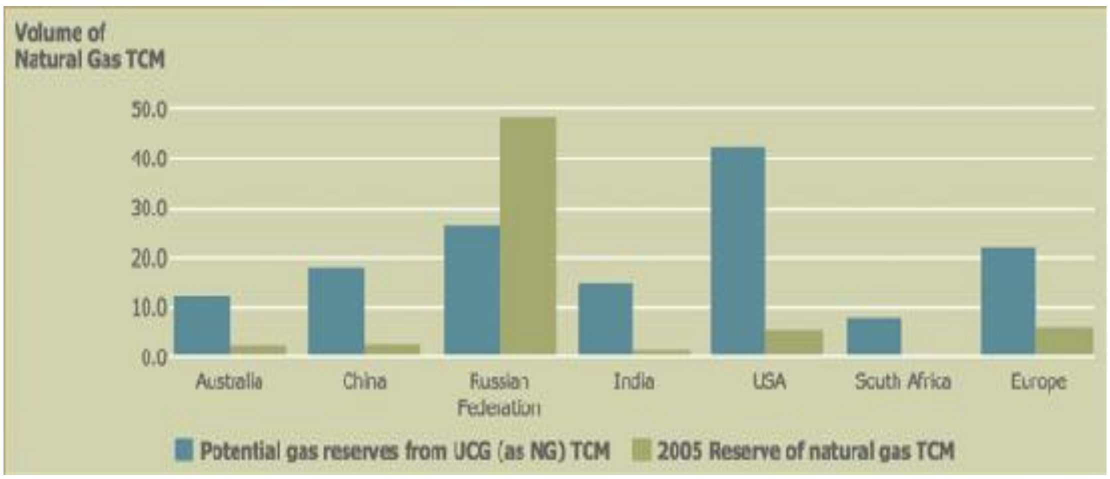


Table 4. Depicting increased quantities of UCG Syngas available – compared to Natural gas.

In summation, here are a number of significant economic benefits associated with UCG that include:

- No need for the coal to be mined
- No need for coal handling
- No need to transport the coal
- No need to prepare the coal to be fed into a reactor
- No need for disposing of ash or slag
- No need for an above ground gasification plant
- Significantly lower capital cost for plant development than surface gasification[11].

Global UCG projects and Commercialization Efforts.

The Russian Republic (Former Soviet Union- FSU) . The earliest and most extensive work on UCG was in the Former Soviet Union. The FSU formed some of the first institutes dedicated to coal utilization in the early part of the 20^{th} century- the Donetsk Institute of Coal Chemistry and Skochinsky Institute of Mining [2]. These institutes run research and development programs during the 1930s, in competition with the Germans who were developing the Fischer-Tropsch technology at the time. Pilot tests in the early 1930's were followed by commercial UCG power plants in the 1940's in the Moscow and Donestsk coal basins. This work gradually developed into the Soviet Union having five industrial scale UCG plants by the early 1960's. However, this work has declined in focus and value due to the discovery of extensive natural gas resources resulting in a downgrade of the Soviet UCG program. As a result, by 2004 only two of the five sites, at Angren and Yuzhno-Abinsk sites have continued operations. The FSU did most of their work on shallow coal seams at less than 600 ft using the vertical wells method less effective in terms of economics and the environment especially with regards to water table contamination and gas seepage. However, work done previously in the Soviet Union has served as a prelude to the current variations of UCG technologies being developed all over the world.

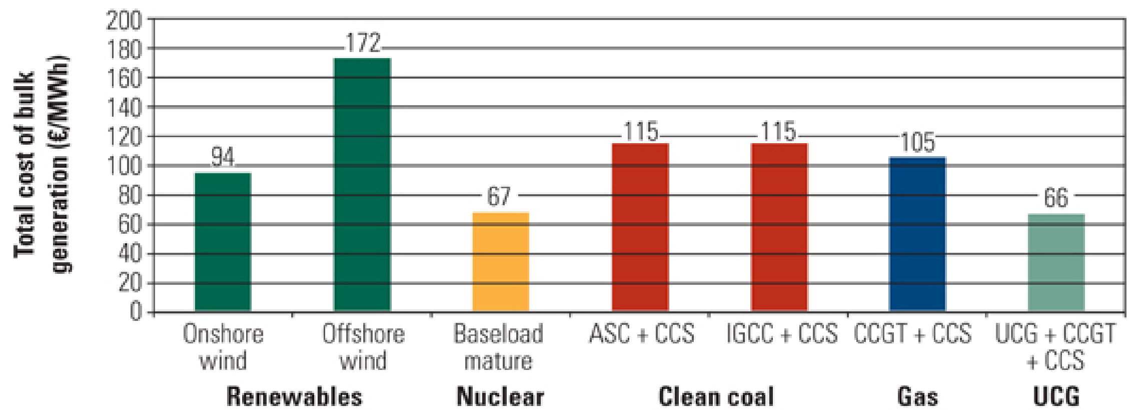
Republic of South Africa (RSA)- Majuba Power plant. One of the largest and most advanced users of Coal technology, the RSA has an Eskom 4100 MW coal fired utility plant at Majuba that has been investigating UCG since 2001. Using Ergo Exergy's UCG technology, this pilot program is currently generating 15,000 m^3/ hr of gas with the intent of evaluating a business case for UCG feasibility as an Integrated gasification and combined cycle (UCG-IGCC) [10] facility. On January 20, 2007, Ergo Exergy published a report that the Eskom plant in Majuba had started the largest commercial UCG to electrical power generation facility in Africa. This case study was significant in that the coal seams being used for UCG were from mines that had been shut down due to excessive mining and maintenance costs. As such, the same study will be used as a benchmark for other un-mineable coal resources in South Africa. As one of the world's largest leaders in coal gasification and Gas-to-Liquids (GTL) technology, the RSA is equipped with the best possible infrastructure for overall UCG integration with other proven state-of-art technologies like IGCC with CCS and GTL through the Fisher-Tropsch (F-T) process. The largest scale implementation of F-T technology are a series of plants operated by another company, Sasol in South Africa, one of the world's leading developers of coal gasification and CTL technology.

The United States (U.S). The United States is the largest user of petroleum fuels for the transportation and electrical infrastructures, whose crude oil is imported mainly from foreign sources. Upward pressure on crude oil prices in the early 1970's and late 1990's boosted interest in increased coal usage to include UCG among emerging clean coal technologies. Amongst the premiere UCG authorities in the U.S are Ergo Exergy Technology and the Lawrence Livermore National Laboratory were the CRIP technology was developed. However, Ergo Exergy Technology continues to stand out as one company whose proprietary technology, eUCG, is at the forefront of many domestic and global projects. Currently, Ergo's eUCG technology is involved or has been co-licensed to some of the largest projects in the world for example; the Eskom-Majuba UCG project in RSA, co-licensed to Linc Energy at the Chinchilla project in Australia, the Hunly project in New-Zealand, Stone Horne Ridge in Alaska, projects in India, the U.K, Canada and to various other sites in the U.S. There have been in excess of 30 pilot programs for UCG in Wyoming, Texas, Alabama, West Virginia and Washington, spearheaded by the Department of Energy (DOE), National Energy Technology Laboratory (NETL) and Lawrence Livermore National Laboratory (LLNL). Alabama was were some of the earliest UCG tests were done from around 1947 – 1960. Lawrence Livermore National Lab and Sandia National Lab under the DOE conducted pilot UCG tests in Wyoming and Washington at several sites from 1973 – 1989, with the most significant being at Rocky Mountain in Hanna, Wyoming from 1986 – 1988. According to the NETL and LLNL, composition of the pilot test data from these test sites has allowed for a bench mark policy formulation for managing UCG technology in the U.S [24]. Amongst the issues identified by the LLNL from tests at Hanna, WY were ground water contamination, gas leaks and ground subsidence. However, just like the Former Soviet Union (FSU), the emergence of vast natural gas resources using hydro-fracking technology is impeding UCG development and implementation. Policy uncertainty is another factor in disfavor of UCG.

China. The emergence of China as a world manufacturing center has only added to the global strain on crude oil. China has the third largest deposits but is also the world's largest miner and user of coal. Most of China's energy needs, over 70% are currently being met by resources from coal followed by hydro-electricity far behind at about 24% [16]. Because of the high demand for coal, surface and underground mining are the main sources of accessing this resource. Surface gasification and open air combustion of coal have created serious environmental problems for both the ground and air in China. According to a 2007 World Bank report, China had more than half of the 20 most polluted cities in the world- making environmental degradation a national priority. UCG provides the best way in adopting clean coal technology to mitigate air pollution, surface contamination, reduced investment and mining costs. As such, China is aggressively pursuing and has conducted 16 large scale UCG pilot projects since 1985. In addition, there is a plan to gasify 17 abandoned coal mines, making it the largest global pilot UCG program to date. [10]. Consequently, Chinese engineers have sought the most patents in UCG so far, a confirmation of their intent in advancing this technology due to their enormous industrial energy needs. Currently, the Xin Wen coal mining group in Shandong Province has six UCG reactors producing syngas for cooking , heating and hydrogen production. Another project in the Shanxi Providence uses the gas for ammonia and hydrogen production. These projects exceed any others commercially available any where in the world so far.

Australia. With vast amounts of coal, Australia is taking advantage of developing their natural resource to produce CTL or GTL fuels economically. As a result, the government sponsored the largest UCG pilot program to-date at the Chinchilla project in partnership with Linc Energy using technology provided by Ergo Exergy. The project involved about 9 injection and production wells plus 19 monitoring wells where 35,000 tons of coal was gasified with 75% total energy recovery in the production gas [10]. Amongst the highlights of this project was the demonstration of a large scale control process in a start and shut down UCG process and environmental performance. Of specific note were findings that no significant ground water and surface contamination was noted nor was there any observation of surface subsidence [8]. The success of the Chinchilla project has allowed for this project to move from a test project and advance to the stage of completing a coal Gas-to-Liquids pilot that has successfully produced ultraclean diesel and aviation fuel.

Some of the largest oil producing corporations like British Petroleum (BP) are also getting involved. In November of 2006, BP showcased their UCG and integrated GTL technologies at a workshop in Kolkata, India. In June 2007, BP signed a technical alliance agreement with Ergo Exergy for a cooperative UCG project. Other nations including the European Union, India, Canada and New-Zealand are implementing UCG Pilot programs as part of their overall energy policy strategy.



Notes: ASC = advanced supercritical, CCGT = combined-cycle gas turbine, CCS = carbon capture and storage, IGCC = integrated gasification combined-cycle, UCG = underground coal gasification.

5. A cost-effective option. This cost estimate shows UCG to be competitive with existing mature coal- or natural gas–fired electricity generation technologies. Note that 1.00 Euro = $1.4320 USD, May 2011. For UCG, no payment for the value of coal is included, and the cost of UCG includes the cost of 90-plus% carbon capture and storage. *Source: UCG Association*

Table 5: Showing an approximated comparative cost of UCG production [5].

Policy uncertainty: Policy risks due to the uncertainty of CO_2 regulation have impeded the development and full implementation of technologies such as UCG and CCS. Government policy is slow and lags behind in making a decision to regulate CO_2 after several decades of deliberation. Of great concern is the coal ash that piles up in barricaded pools at utility plants not classified as a toxic substance although its known to contain heavy metals and carcinogenic contents regulated by the EPA. As a result, the true cost of coal to electrical production is not fully captured due to these environmental exclusions. In the U.S, there is no existing regulation that covers specific legal framework for UCG development. Areas suitable for UCG investigation usually overlap with already existing energy sources like oil and natural gas exploration which complicates devising specialized policy for UCG technology by itself. Policy initialization has been investigated by the NETL on behalf of the DOE. Other policy suggestions include adopting some of the available regulations under the Coal Mines Naturalization act of 1973 in conjunction with the Clean Air and Water acts. With policy implementation and proper EPA enforcement, technologies like UCG and CCS will be part of responsible coal usage. However, the artificially low coal-to-electrical production of about $ 0.03 per KWh impedes pollution control and other competitive energy resource technologies like UCG from fruition.

Environmental aspects of UCG.

Underground gasification has some significant environmental benefits over conventional surface mining and gasification which include the following:

- Minimal land use. The absence of surface mining from which no soil or overburden removal is necessary to extract the coal. As such there is no requirement for any reclamation activity. This reduces land dormancy from the time it undertakes UCG activity to when it can be used for food production and human habitation.
- Significantly reduced use of groundwater or freshwater for which underground saline water is used. Lignite coal has higher water content in its rock formation and as such less water is required during the gasification process.
- Less environmental impacts traditionally associated with coal mining and handling, especially related with the disposal of Coal tar, ash, heavy metals like mercury, Arsenic, Lead. Also, there are significantly reduced air pollutants and nuisance atmospheric particulates like Volatile Organic Compounds (VOC) and coal dust. A substantial portion of the sulfur, mercury, arsenic, tar, ash and particulates found in coal remain underground. No landfill disposal is required for the coal ash or slag [11].
- If Coal seams are to be to be gasified they should be located far below the water-table to avoid contamination or seepage depending on the hydrology of the site. For example in Texas, according to the Water Development Board, water tables vary from 100 ft in the south to more than 600 ft in the north west areas of the Ogallala aquifer which extends northwards into other states north of Texas.
- Any sulfur or metals that reach the surface do so in a chemically reduced state, making them easier to remove. Also UCG provides significantly increased overall energy production per unit mass or volume of generated pollutants.
- UCG seams left behind from gasification can provide potential sites for Carbon capture and storage (CCS). Carbon sequestration is an important process in reducing environmental CO_2 from combusted fossil fuels were storage can be done safely at great depths beyond 1000 ft.

Product gases.

Carbon dioxide contributes significantly to global climate disruption. It's generated during combustion of fossil fuels and in surface or underground gasification process i.e., as part of the water shift reaction used to produce syngas. Current climate mitigation provides an opportunity to capture and compress CO_2 for underground storage or for transport in a pipeline for usage in enhanced oil recovery (EOR) projects. Underground gasification provides cavity space vacated by the combusted coal into syngas, which cavities can be utilized as storage locations for CO_2 capture (CCS). For safe storage the cavities have to be in geologically sealable rock formations, like sand-stone or other cap-rock, that will not allow the CO_2 to permeate upwards into the groundwater table. As indicated earlier, gasification of coal seams at depths significantly removed from the water table by several hundred feet help mitigate this risk. Current studies by Dr. Friedmann et al at the LLNL and the Aachen group in Germany have made similar conclusions regarding the ability for evacuated coal seams to store CO_2. According to Aachen group "The central idea, which requires further study, is that UCG turns the coal left behind into the rough equivalent of activated carbon, riddled with a vast network of internal pores" [18] eager to capture CO_2. This seems to support the idea that underground evacuated seams are good candidates for CCS, making UCG an attractive option in reducing CO_2, a green-house gas. However if CO_2 leaks into the water table, it could react with water to form carbonic acid or bring with it traces of SO_2 forming Sulfurous acid introducing other environmental problems into the water table.

Gases from underground gasification CO, H_2, CO_2 and H_2S can be easily separated on the surface using pollution control processes like Amine gas treatment or pressure swing adsorption (PSA). By applying different absorbents and pressure gradients, specific gases can be preferentially removed. A Flue gas desulfurization unit is required to remove SO_2 from combusted fuels that contain H_2S. The desulfurization process is important as it significantly removes the pungent H2S smell in 'gas sweetening'. Also, this process reduces acid degradation reactions from the aqueous amine solutions needed for efficient CO_2 removal to prevent corrosion of equipment. Commercially, CO_2 can be used in the oil and gas industry for EOR or as a fluid for enhancing rock fracturing in the syngas or natural gas recovery process. Also, Gypsum- $CaSO_4.2H_2O$, a by-product of H_2S removal in the FGD unit during gasification has a commercial value in the building and construction industry. Additionally, if N_2 gas from air feed combustion is limited to minimize nitrogen oxide- NOx emissions, its product of N_2 and H_2 gas in the syngas product can be commercially valuable in the manufacture of ammonia based fertilizers and chemicals. Most important is the conversion of CO_2 by plants using photosynthesis, sunlight and water to make carbohydrates which are the basic energy sources for both plants and animals.

Site Identification and Selection.

The success of a UCG project for either pilot or industrial purposes relies on the proper identification and selection of a geological site that minimizes environmental risks while maximizing the economic benefits. Environmental hazards include, but are not limited to minimizing groundwater contamination, ground subsidence, underground explosions and controlling UCG from having to burn uncontrollably. As such, site monitoring is essential to ensure the protection of natural resources, local population and other bio-systems. Thus, in-place monitoring equipment and techniques are essential to detect burn progression, cavity development and contaminant migration.

From site study of the Chinchila UCG project in Australia, an important component in minimizing contamination was to keep the gasifier pressure lower than the surrounding strata. When reactor pressure of the gasifier is less than hydrostatic pressure, there is no driving force for flow into the surrounding strata. During geologic and site preparations for this project, levels of heavy metals like mercury, arsenic, lead, VOC's- benzene and toluene in the ground, water-table and air were sampled to establish a base line. These pollutants were monitored periodically during combustion phases of UCG production at different locations of the production wells. Contaminant levels of all these pollutants were found to be within regulatory requirements for the ground, water and air at the Chinchilla site and in the surrounding areas during and at the end of the pilot project. Additionally, no ground subsidence was noticed at this demonstration test site. On the other hand, inadequate geologic tests and site selection was a major cause for poor results from the Hoe Creek project in Wyoming.

Environmental Issues with UCG.

However, UCG technology does present its own challenges which include;

- **Ground water Contamination.** Underground gasification requires no above ground disposal of coal combustion wastes and contaminants of heavy metals- most of which remain underground. As a consequence, these contaminants are left behind in the coal seam with the possibility to leach into the surrounding water table if the seam is right below the water table as shown in figure 8.

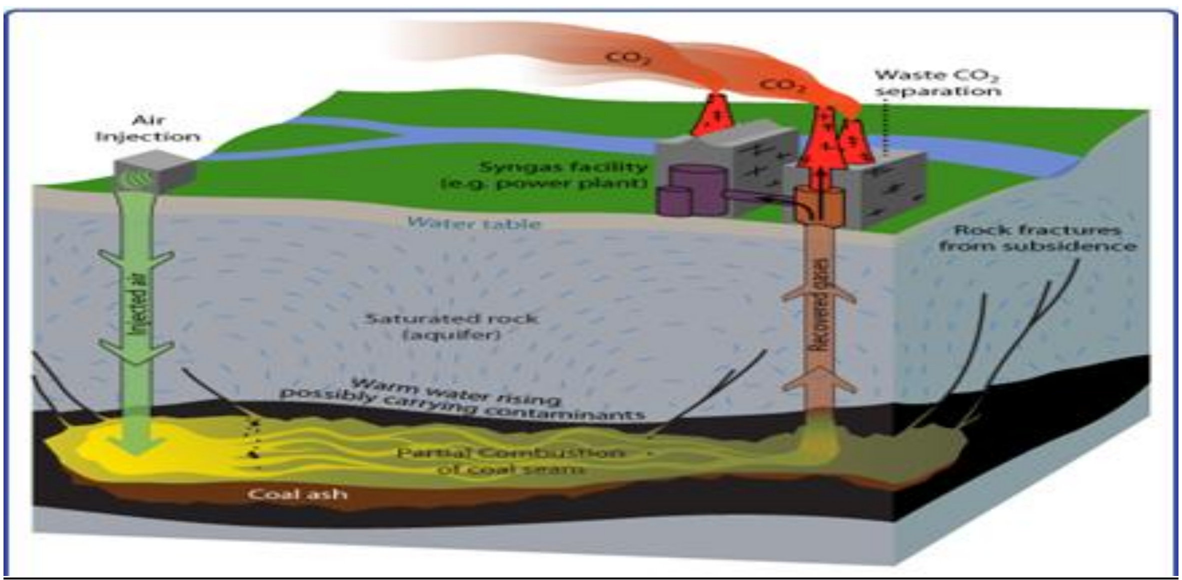


Figure 8: UCG process with possible water contamination due to site proximity.

Increased reactor temperature with adjourning rock increases the transport properties of the pollutant species upwards towards the groundwater closer to the surface. Temperature gradients of neighboring rock could also change the permeability of the reservoir rock. The way to mitigate this is to choose very deep sites with natural geologic seal rock formations or pressure gradients less than hydrostatic pressure to avoid gaseous and contaminant migration [12]. Earlier UCG work especially in FSU and at the Hoe Creek pilot project in U.S indicated factors that lead to water table contamination. These factors included shallow coal seams, poor rock sealing units and an over-pressurized burn cavity greater than hydrostatic pressure as confirmed in a study by Jane Long et al at the LLNL [17].

- **Subsidence.** This process occurs when the ground or a particular land mass collapses over an area where underground mining, drilling or extraction is or has occurred. Also referred to as an 'overburden deformation', subsidence is a likely consequence of UCG or other mining activity. In the case of UCG, the supporting underground coal mass is combusted during gasification leaving a void space. Thickness of the extracted coal seam, strength of the seam cover and surrounding rock strata are factors that determine the magnitude of subsidence. Geology and Mining engineering are subjects that extensively cover the mechanical limitations of rock formations and can perform predictive modeling for subsidence on a prospective UCG site. Usually, the development of fractures within the seam rock cover is an indication that the product gas will be lost to the surrounding rock strata. Additionally, over pressurization of the gasifying reactor will increase the fracture geography and creep upwards towards the surface collapsing inwards as indicated in the figure below.

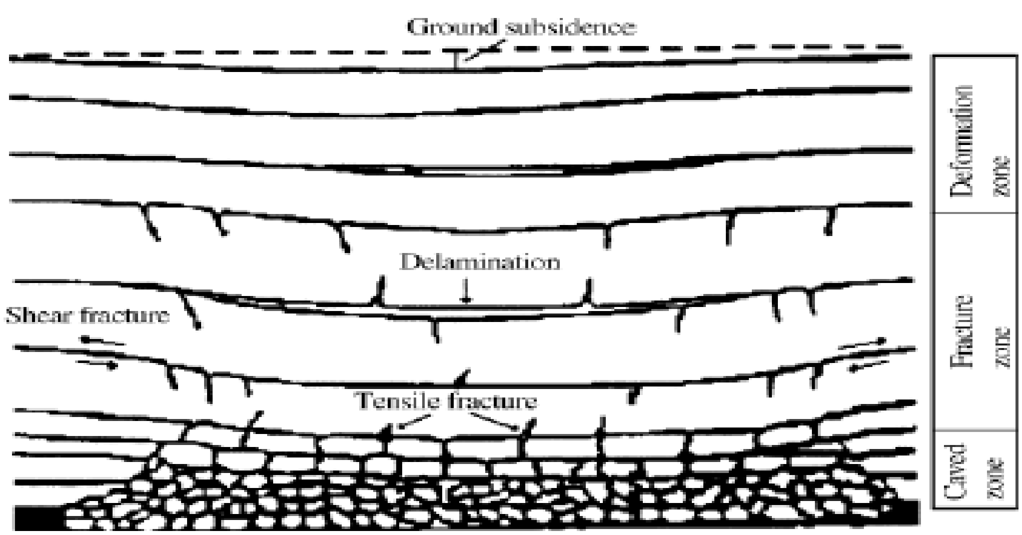


Figure 9: Shows possible mechanism of subsidence. (Kelly et al., 2002) [12].

- Consequently, subsidence can potentially change the flow of the underground water table. The extraction width of the coal seam can also play a role in increasing the magnitude of fractures in the overburden as determined by scientists at Linc Energy studying factors that cause subsidence during UCG. In this study the extraction width increased the possibility of subsidence as indicated in figure 10.

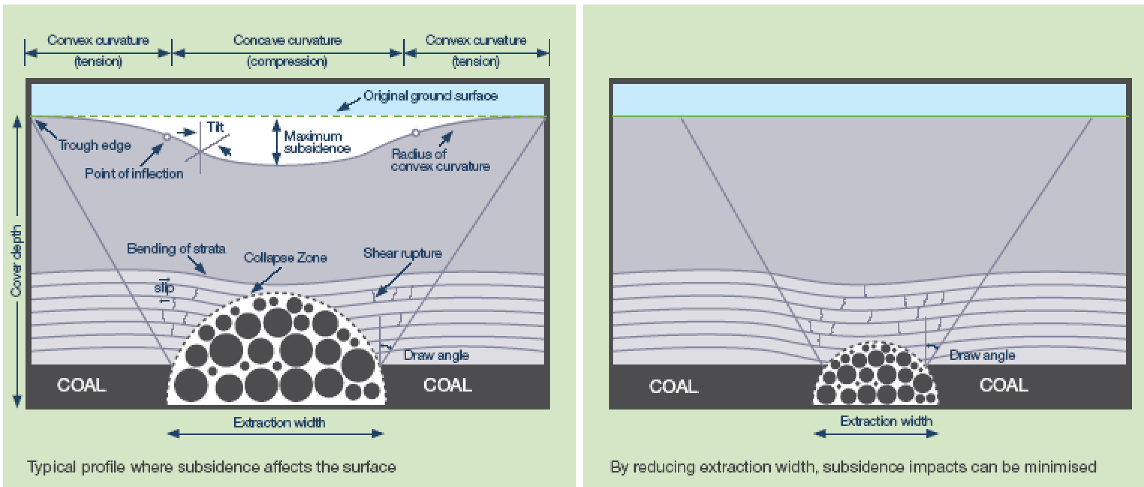


Figure 10: Subsidence as a function of extraction width [19].

- **Negative production effects.** Mischaracterization of the process conditions or the geology can lead to poor results like at the Hoe Creek project in Wyoming. In this particular instance, too much water lead to a flooded reactor, mechanical failures and subsidence. In the case of too much water, it leads to premature termination of gasification due to the energy burden to vaporize the excess water. As a consequence, the needed activation energy for the necessary syngas reactions to proceed is not available. Mechanical problems lead to hydrologic problems were premature fracturing leads to a loss of gas and contributes to the occurrence of subsidence. Another problem, is over –ignition of the seam which can lead to an uncontrollable fire burning within the seam. Additionally, it is possible to start another fire unknown or unintended in a separate coal seam connected to an ignition point due to a fractured seal. This was the case in Columbia county, Pennsylvania, were an underground seam fire started in 1962 is still burning today. Accidental underground coal seam fires that burn uncontrollably for long periods of time that no one can stop result in additional environmental and safety problems.

Conclusion.

Underground Coal Gasification is a technology that has received a lot of interest, partly in response to increasing crude oil prices and an emerging trend in tighter global environmental regulations. In UCG, a variety of coals preferably Lignite, that sits in deep seams or abandoned mines, inaccessible for conventional mining become an economic reality. Syngas, the product gas of underground gasification, can be an economic and practical energy resource serving both the energy and transportation sectors. The energy sector can use Syngas, Methane or Hydrogen gas, all products of UCG, to generate electricity using steam turbines. On the other hand, CTL or GTL using the Fisher-Tropsch process can create clean ultra-low emission liquid fuels for the transportation sector beneficial to the environment and engine performance. Reduced emissions from utilizing UCG address environmental mitigation of coal pollutants like coal ash, heavy metals and CO_2, while generating power when integrated with other state of art technologies like IGCC. As such, the opportunity to co-produce power and premium quality transportation fuels with chemicals, offers the best prospects for utilizing unusable or un-mineable coal while maximizing the economic and environmental benefits.

Therefore in conclusion, UCG has other advantages of over SCG that include the suitability of using product gases like hydrogen and methane as feed stock for the plastics, fertilizers and Hydrogen fuel-cell economies. As such, UCG is destined to provide an important element in the new era in which coal, with greater proven reserves than oil, will rival the existing dominance of oil in the global energy markets, allowing for responsible coal utilization and revitalization through increased synthetic fuels to reduce reliance and capital outflows on imported crude oil. Savings can be used for domestic infrastructure improvements, job creation, energy diversification, reduce deficit spending and most importantly- relieve pressure from increasing crude oil prices.

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