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ORIGINAL RESEARCH PAPER

An Overview of Underground Coal Gasification

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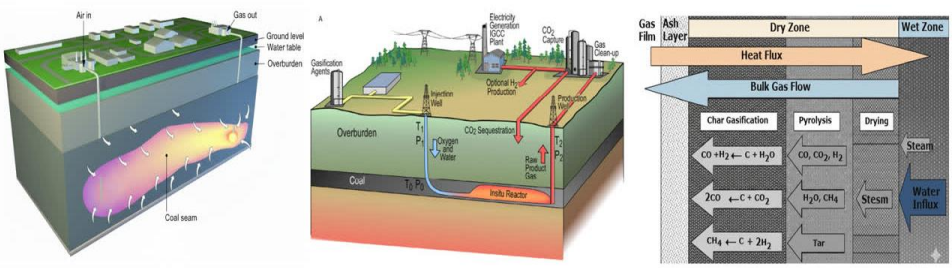
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A B S T R A C T

Underground coal gasification (UCG) represents a promising and cleaner approach to harnessing unmined coal reserves, offering a viable alternative to traditional coal extraction methods. While conventional mining recovers only 15-20% of total coal reserves, UCG has the potential to significantly extend the life of global coal resources by accessing otherwise unrecoverable deposits. Traditional mining is resource-intensive, requiring substantial time, labour, and machinery, and poses environmental and safety challenges such as landscape disruption, high operational costs, and risks to personnel. UCG circumvents these issues by gasifying coal in situ through a network of wells, where the coal is ignited and sustained by injected oxidants, producing syngas—a mixture primarily of carbon monoxide and hydrogen. This syngas can be used for industrial heating and power generation or converted into hydrogen, synthetic natural gas, and liquid fuels. Compared to surface mining and gasification, UCG offers lower capital and operating costs, lower greenhouse gas emissions, and can be integrated with carbon capture and storage (CCS) technologies. With increasing global energy demand, oil and gas reserves depletion, and growing concerns over climate change, interest in UCG has risen worldwide. The process holds immense potential to exploit low-grade, inaccessible coal seams and convert them efficiently into syngas, with wide-ranging applications in energy, fuel, and chemical production. This report comprehensively analyses UCG technology, tracing its evolution and key projects globally. It examines site selection criteria, highlighting the importance of coal geology, coal properties, and geological and hydrological conditions. The report also reviews various UCG methods and the chemical and physical processes involved, and explores process optimization and the influence of different operational parameters. Furthermore, the environmental and economic implications of UCG are assessed, alongside its advantages and disadvantages. This paper is an in-depth review of the fundamental concepts and technologies driving UCG, offering a detailed insight into this evolving coal conversion method.



1. Introduction

Coal is a non-renewable fossil fuel formed from plant remains over 100-400 million years ago. It is the most abundant fossil fuel and has been a critical energy source for around 300 years. Although it was mined in Europe in the 13th century, it was not a highly desirable fuel because of its toxic combustion products. Coal became a vital fuel source at the beginning of the Industrial Revolution. The most significant challenge in the coal industry is removing organic sulphur chemically bound to the coal. Traditional methods of burning coal produce emissions that can reduce air and water quality. Clean coal technologies remove sulphur and nitrogen oxides before, during, and after coal is burned or convert coal into a gas or liquid fuel. Coal gasification, a clean coal technology, bypasses the conventional coal-burning process by converting the coal into a gas. This process removes sulphur, nitrogen compounds, and particulates before the fuel is burned, making it as clean as natural gas.

Coal was first used in gas production during the late 18th century. Early production was mainly used for lighting, but as gasification techniques improved, applications grew wider. By the 19th century, coal conversion to gas was a well-established commercial process. Globally, coal will remain an indispensable chemical feedstock and energy source for an extended period. The assumption that coal will stay cheap for decades supports investment in 'clean coal' technology and trumps serious efforts to increase energy conservation and develop alternative energy sources. Underground Coal Gasification (UCG) is a promising option for the future use of unworked coal. Current coal gasification technologies, such as entrained flow, fluidised bed, and moving bed, use a surface reactor for gasification. An alternative to a surface gasifier is an underground coal gasifier [1].

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Underground coal gasification (UCG) is an advanced energy extraction process that involves converting hydrocarbon materials (coal) into a combustible gas (synthesis gas/syngas) while it remains underground. It is a gasification process used to produce gas from coal underground by injecting air or oxygen into non-mined coal seams and extracting the product gas via surface wells [2]. It is sometimes referred to as in-situ coal gasification (ISCG). Unlike traditional coal mining, where coal is extracted and processed, UCG involves igniting coal seams deep beneath the Earth's surface and injecting air, oxygen, and sometimes steam to facilitate gasification. UCG utilises the same fundamental chemical reactions as conventional surface coal gasification reactors to carry out the gasification process. The gasification process occurs directly within the coal seam underground rather than in a manufactured gasification vessel or plant on the surface. It is also a method used to recover the coal feedstock that is not economically available through conventional coal recovery techniques. The coal seam acting as the reactor itself has a cost-saving benefit as well as the advantage of not requiring the coal to be mined to be gasified [3]. The method also lowers the capital investment by eliminating the need for specialised coal processing (transportation and storage).

UCG is achieved by injecting steam and air (oxidant) into the coal seam, which is then ignited to initiate gasification. Typically, elevated temperatures are essential for initiating and sustaining the gasification process. The products and by-products of gasification vary depending on the nature of the coal, the temperature, the pressure, and whether air or oxygen is used. The product gases (syngas) consist primarily of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4) and to a lesser extent, hydrogen sulphide (H_2S), as well as some higher molecular weight pyrolysis products [4]. The products flow to the surface through one or more production wells located ahead of the combustion zone. The resulting syngas can be used to produce electricity, chemicals, liquid fuels, hydrogen, and synthetic natural gas. The primary purpose of underground coal gasification, regardless of the method used, is to obtain the energy contained in the coal for use on the surface without mining in the usual sense.

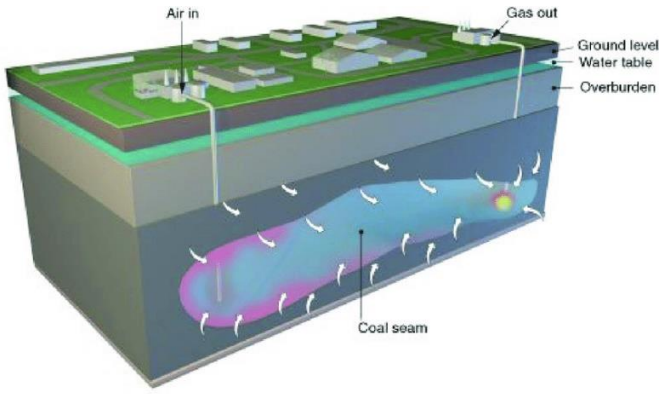


Figure 1. Schematic of the UCG process (linked vertical wells method), with water entering from the surrounding rocks [5].

This report provides an in-depth overview of Underground Coal Gasification (UCG), detailing its historical development, notable projects, and technological advancements. It explains the UCG process, including the chemical and physical reactions involved, and outlines methods for optimizing gasification efficiency. Additionally, the report explores the factors influencing UCG operations and assesses its environmental impacts, weighing the benefits and drawbacks of this energy extraction method.

2. Literature Review

2.1. Historical Background and Evolution of UCG

The concept of underground coal gasification originated with German scientist Sir William Siemens in 1868, who proposed its use in England. Simultaneously, Russia's Dmitri Mendeleev suggested controlled underground coal burning using injection and production wells. By the beginning of the 20th century, many cities were covered with smoke from the side effects of the Industrial Revolution. The Nobel laureate Sir William Ramsay led practical attempts to implement UCG, but World War I halted efforts. The initial goal of UCG was to reduce the physical burden on coal miners [6].

Over the past century, significant experiments in UCG have been conducted, with the first commercial process occurring in the Soviet Union in 1961. Since the beginning of this century, UCG has been identified as an important source of energy in the context of a low-carbon economy, and UCG projects have set off a new upsurge [7]. Before 2000, most UCG tests took place in the Soviet Union, the US, Europe, and China, while post-2000, Australia, South Africa, and China took the lead. Canada has been in partnership with the US, and by reference to its UCG technology, through continuous self-development and field experiments. The technology represents the mainstream of UCG technology in Western countries and has been applied directly or indirectly in UCG tests in Australia, South Africa, India, China, and other countries. Australian underground coal gasification has been based on Canadian technology. Australia has the most complete industrial chain of UCG tests. South Africa has launched coal liquefaction projects and has some coal chemical industrial bases. However, Canadian UCG technology directly or indirectly influences its UCG technology. During 2006-2012 in South Africa, relevant industrial tests were carried out in Eskom and other areas, and more industrial tests on a much larger scale were planned to be implemented. However, substantive work has yet to be carried out [8]. These experiments involved coal seams ranging from 0.3 to 1.8 meters thick and depths of 11 to 1400 meters, focusing on lower-quality coals that are difficult to access or unsuitable for traditional mining [6]. Figure 2 illustrates the number of research and development projects of UCG worldwide.

Currently, countries ready for UCG technology research include Britain, Pakistan, Bulgaria, Vietnam and Poland; the EU, India, and other countries and regions are focusing on developing this technology. The potential for UCG to access low-grade, inaccessible coal resources and convert them commercially and competitively into syngas is enormous, with potential applications in power, fuel, and chemical production.

2.2. Coal Combustion Properties

Coal combustion consists of three distinct phases, which are similar in both conventional and unconventional (in-situ) coal gasification processes:

1. **Preheating phase**: flammable gases evolve when the coal fuel is heated to its flash and fire points. This is similar to dry distillation.
2. **Distillation or gaseous phase:** When the mixture of evolved flammable gases and oxygen is ignited, energy is produced in heat and light. Heat transfer from the combustion region maintains the generation of flammable vapours.
3. **Charcoal phase or solid phase**: the output of flammable gases from the material is too low for the persistent presence of flame, and the charring/charred fuel no longer burns rapidly but glows and later only smoulders [9].

Coal burns in oxygen in complete combustion, producing mainly carbon dioxide and water. When coal burns in the air, nitrogen from the air also reacts, forming nitrogen oxides. Other elements in coal, like sulphur and iron, yield their respective oxides, such as sulphur oxides and ferric oxide (Fe^{3+}). Combustion reactions produce a range of chemical species as they reach equilibrium. Incomplete combustion occurs when there isn't enough oxygen for the coal to react fully, resulting in products like carbon monoxide, hydrogen, soot, and nitrogen oxides. Incomplete combustion can happen when the combustion front is quenched by a heat sink or disrupted by a mixture that's too rich or lean in fuel and air.

2.3. Geological Requirements For UCG

The selection criteria for a potential UCG site are a challenging factor for UCG technology in different locations around the world. Coal deposits in various regions worldwide differ in their geological setting and other natural coal properties; thus, UCG sites are unique from place to place. Natural factors also play a role among the criteria of seam selection for a successful UCG process. These factors include seam geology, physical and chemical properties of coal, the nature of the surrounding rocks and the geo-hydrological condition of the area under consideration [10]. It is also essential to consider the overburden material (the rock and soil above the coal seam) and any aquifers around the area. A potential ideal UCG site should be free of any surrounding water bodies, as any unwanted water influx would lead to compromised gasification efficiency.

Site selection is critical for the success of a UCG project. A thorough understanding of the coal seam's characteristics, the permeability and fault structure of the surrounding strata, and the area's geology and hydrogeology is essential. This involves drilling pilot boreholes to the coal seam for coring and characterisation and conducting a high-quality seismic survey (ideally 3D) of the entire site. Additionally, hydrogeological modelling is necessary to meet groundwater regulations in most countries [3]. Table 1 illustrates the primary projects of overseas UCG in the 20th century.

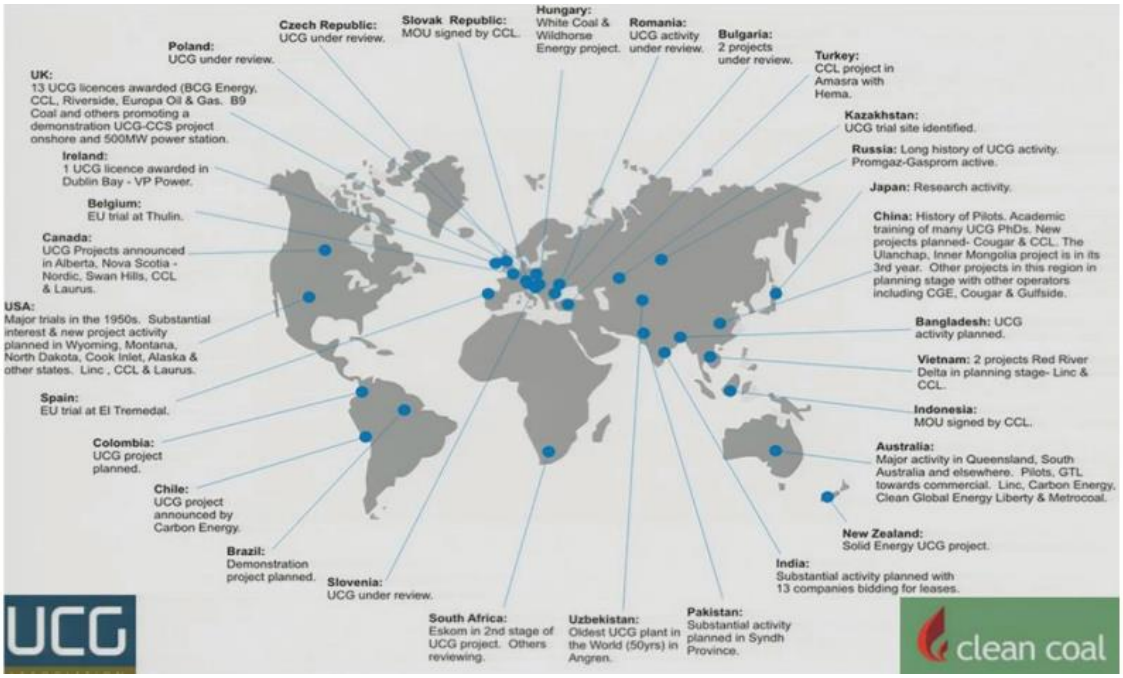


Figure 2. Number of research and development projects of UCG worldwide [6].

Table 1. Primary projects of UCG in the 20th century [7]

Test Site	Country	Year	Seam Thickness (m)	Seam Depth (m)	Coal Gasified (ton)
Lisichansk	Russia	1934-1936	0.75	24	-
Lisichansk	Ukraine	1943-1963	0.4	400	-
Gorlovka	Russia	1935-1941	1.9	40	-
Podmoskova	Russia	1940-1962	2	40	-
Bois-la-Dame	Belgium	1948	1	-	-
Newman Spinney	UK	1949-1959	1	75	180
Yuzhno-Abinsk	Russia	1955-1989	2-Sep	138	2×10^6
Angren	Uzbekistan	1965-now	4	110	$\geq1\times10^7$
Hanna 1	USA	1973-1974	9.1	120	3130
Hanna 2	USA	1975-19719766	9.1	84	7580
Hoe creek 1		1977	7.5	100	112
Hanna 3	USA	1977	9.1	84	2370
Hoe creek 2A	USA	1977	7.5	100	1820
Hoe Creek 2B	USA	1977-1979	7.5	100	60
Hanna 4	USA	1979	9.1	100	4700
Hoe creek 3A	USA	1979	7.5	100	290
Hoe Creek 3B	USA	1979	7.5	100	3190
Princetown	USA	1979	1.8	270	350
Rawlins 1A	USA	1979	18	105	1330
Rawlins 1B	USA	1979	18	105	169
Rawlins 2	USA	1979	18	130-180	7760
Brauy-en-Artois	France	1981	1200	-	-
Thulin	Belgium	1982-1984	860	-	-
Centralia Tono A	USA	1984-1985	6	75	190
Centralia Tono B	USA	1984-1985	6	75	390
Haute-Duete	France	1985-1986	2	880	-
Thulin	Belgium	1986-1987	6	860	57
Rocky Mountain 1A	USA	1987-1988	7	110	11200
Rocky Mountain 1B	USA	1987-1988	7	110	4400
El Tremedal	Spain	1977	2	600	-

Table 2. Primary UCG projects in the 21st century [7]

Countries	Year of Project Commencement	Objective
China	2011	Power generation H2 for fuel cells
India	2005	Power generation: Study and evaluate the calorific value of the gas generated
Pakistan	2009	Power generation
USA	2005	Natural gas liquefaction, developing 3D cavity growth simulators
Australia	2007	UCG-CGS, UCG-IGCC power generation
Poland	2007	Environmental and safety issues related to UCG processes

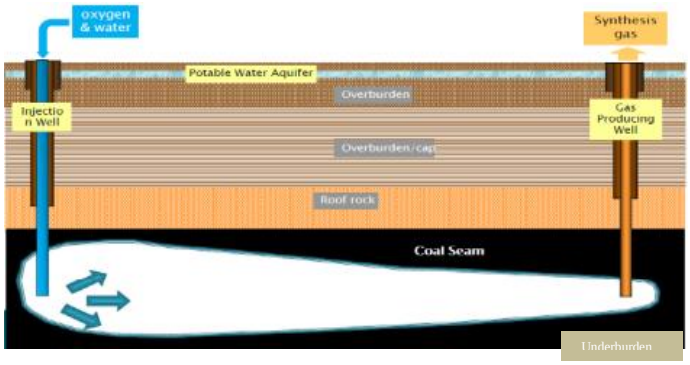


Figure 3. UCG geological interaction [11].

The groundwater regimes must be adequately defined within and around the site of the selected operation. The oxidant injection pressure and the UCG chemistry can be impacted by groundwater influx. Groundwater contamination is one of the significant challenges that hinder UCG operation. During any phase of the UCG process, surrounding water bodies may become polluted by the products of the chemical reactions occurring within the coal seam. Many of these products are considered to be environmental hazards [11].

2.3.1. Geological Exploration for UCG

Exploration is crucial for selecting a UCG site as it helps assess the nature of the coal deposit and the geology and geohydrological conditions of the area. The data gathered from exploration determines whether the site is appropriate for the UCG process. Various exploration techniques are used to evaluate the subsurface condition of the target area. These may include geophysical wire logging. In this technique, a borehole is drilled, and wireless probes are inserted through the borehole underground. The physical properties, such as lithological boundaries, rock type, and rock strength of the subsurface formation, are determined. The cost of exploration in UCG depends on the quality and quantity of the data as well as the complexity of the geological conditions.

Geological exploration for a suitable UCG site consists of the following steps:

- Geological mapping of individual coal seam, overburden and floor rocks, and intervening shale units.
- Coring the complete coal interval, including the roof and floor rock, accompanied by detailed descriptions.
- Laboratory analysis, including petrography, volatile content, qualitative and quantitative determination of the inorganic components, calorific value, porosity, permeability, compressibility, gasification reactivity of the target coal, and, eventually, distribution maps of the analytical data to give a complete depiction of coal and roof/floor characteristics.
- Structural features associated with the target interval, such as frequency, continuity, and degree of infilling of joint systems, and other structural aspects, such as folds and faults.
- 3-D modelling of the coal seam objective that combines the information available from laboratory analysis, paleoenvironmental reconstruction and structures with log analysis from oil and gas exploration wells to predict the variability in the coal and roof/floor rocks.
- 3-D seismic survey
- Aquifer pressure and hydrogeological modelling [9]

2.3.2. Coal Seam Properties

Coal deposits and their geological conditions vary widely from one seam to another and from coalfield to coalfield across the globe. Coal seam properties and geological settings determine the potential for UCG operations. They are also crucial in modelling the process and monitoring the operation by predicting the variability of the target coal. Coal properties for UCG can be deduced from the coal seam depth, seam thickness, seam inclination, and coal rank, among other properties.

Coal seams occur in various depths, some shallow while others lie deep within the Earth's surface. The depth of a coal seam is an important parameter in UCG. Coal seams with a depth of up to 300m are considered shallow seams and are generally easy to ignite and, in most cases, are associated with an aquifer. For a successful UCG process, the coal seam must be in a vertical separation of more than 100m from the major aquifer. Hence, conducting the UCG process at a greater depth than a shallow depth to avoid problems like groundwater pollution and land subsidence is preferable [10]. Coal seams at a deeper depth offer greater environmental safety but increase the operational costs and technical challenges, such as temperature control, pressure and gas flow.

Coal seam thickness suitable for UCG ranges between 0.5 and 30m. Thinner coal seams (less than 0.5m) in UCG are problematic as there is a possibility of heat loss to the surrounding formation. Therefore, a moderate seam thickness (more than 1m) is required and preferred for the UCG process [10]. Thicker seams provide larger coal volumes for gasification, but controlling the process becomes more complex, leading to potential uneven burning or cavity formation. Thinner seams require more precision when being gasified and tend to yield less gas. The coal seam thickness directly influences the economic and technical feasibility of UCG.

The coal seam inclination has less of an influence on the process. Dipping coal seams (angle greater than 70°) are easier to sustain and ignite quickly than horizontal seams. Dipping seams are associated with complex geology, making them more suitable targets for UCG technology.

Almost any coal-rank type can be extracted using the UCG process, but low-rank (lignite and sub-bituminous) and non-swelling coals are mostly preferred for the UCG process. Low-rank coals tend to shrink upon heating, thus improving the connection between production and injection wells. The rank of coal affects both its permeability and reactivity. Low-rank coals are more permeable than high-rank coals. The structure and nature of the coal in the coal seam can also influence gasification behaviour, as successful UCG processes depend on the porosity and permeability of the coal seam. Porosity refers to the natural pores formed during coal formation. Permeability is the ability of the pores or cracks present in coals to transport fluid. High-rank coals and coal seams that are deeper have low permeability. The permeability is essential in the gasification process. Cleated and more permeable coal seams are ideal for UCG because they allow for better gas movement. Low-rank coals are characterised by their porous and permeable structures and are especially suitable [10]. Additionally, the coal's chemical composition also influences the gasification reaction. The volatile matter, moisture, and ash content majorly affect the gasification reaction.

A summary of the optimum coal characteristics for the UCG process is listed in Table 1.

Table 1. Optimum coal characteristics.

Optimum Coal Characteristics	
Coal seam thickness	Greater than 0.5m Depth between 30 and 800m Maximum inclination of 70° Predictable continuity
Coal rank	Preferably low rank (lignite and sub-bituminous) due to the content of volatile matter
Reactivity	High reactivity characterised by significant amounts of exinite (liptinite), vitrinite reflectance ≤0.8%, average quantity of vitrinite+exinite ≥60%, volatile matter ≥ 35%, and H/C atomics ratio≥ 0.75%
Calorific value	Relatively high (later stages of lignite and sub-bituminous)
Coal seams, preferably in saturated conditions and not in the groundwater protection zone (unsaturated coals can be considered in particular circumstances)	
Coal seams with inherent permeability (technological processes such as reservoir fracture can increase permeability)	
Mineral matter must be as low as possible, and ash fusion temperature as high as possible (lower Ca, Mg, and Fe content)	

2.3.3. Geological and Hydrological Conditions

The coal layers (seams) underground are enclosed by rock material, which is generally referred to as overburden (strata lying above the seam) and underburden (strata below the seam). The geological and geotechnical conditions of the overburden and underburden strata, as well as the coal seams, will directly influence the UCG process. High-strength yield impermeable strata with low porosity and stable geological structures are the most favourable overlying and underlying coal deposits suitable for UCG processes. They provide a seal between the coal seam(s) and the surrounding rocks, limiting the amount of subsidence.

Hydrology is an essential criterion for the screening of a potential UCG site. Water is required for the UCG process as it is integral to the gasification reaction. Water entry into the reaction chamber is limited to the need for the gasification reaction. If the inflow is too high, it reduces the gasification efficiency or stops the gasification process altogether. If a freshwater aquifer is a few meters above the target coal seam in the prospect site, that site must be abandoned to avoid groundwater pollution. Coal layers to be gasified need to be in a vertical separation of about 100m from the major aquifers [10].

The dependent and independent variables in underground coal gasification are shown in Table 2. Like mining, oil and gas extraction, site selection determines the important independent variables that determine the technical and economic performance.

Table 2. Independent and dependent variables of interest for UCG [12]

Independent Variables	Dependent Variables
Coal properties	Product gas
Proximate analysis	Composition, heating value
Ultimate analysis	Flowrate
Coal seam geology, hydrogeology	Process efficiency
Thickness, depth, and dip	Thermal
Permeability to gas and liquid	Chemical
Strata geology, hydrogeology	Resource recovery
Operating conditions	Interaction with the environment
Injection composition	Water consumption
Injection flowrate	Subsidence
Operating pressure	Dispersion of pollutants
Well layout	

2.4. Methods for UCG

The UCG process involves drilling, linking, ignition, and gasification. The basic layout of the process requires one borehole for injecting gases and one for production [13]. Injection and production wells are drilled apart at some distance from the surface into the coal seam. Two standard methods of preparing a coal seam for gasification have been successfully utilised: shaft and shaftless. The implemented methods depend on factors such as the coal seam's natural permeability, coal's geochemistry, seam thickness, depth, width, and inclination, proximity of urban developments, and the amount of mining desired [14].

Shaft methods use coal mine galleries and shafts to transport oxidants and the UCG product streams into and out of the reaction space. These sometimes require the creation of shafts and the drilling of openings through underground labour. The shaft method was the first technique utilised within UCG systems. The shaft method is only employed in closed coal mines for economic and safety reasons [14]. The following are examples of standard UCG shaft methods:

- **Chamber/ warehouse method**: this method is best utilised for highly permeable coal types. Brick walls separate coal panels, whilst oxidants are supplied to a side of the panel that has already been ignited, and the product is withdrawn from the other side. The chamber method strongly relies on the natural permeability of the coal seam to allow for sufficient oxidant flow through the system [14]. This method produces syngas at low flow rates with a varying composition.
- **Borehole producer method**: the coal seam is separated into parallel horizontal galleries, all connected by a series of boreholes. Remote electric ignition is used in each borehole to begin the UCG process. This method is best used for extremely flat coal seams [11].
- **Stream method**: this method is best utilised for coal seams oriented in a sharp inclination. Parallel-pitched galleries follow the contour of the seam, all of which are connected at the bottom via a horizontal gallery known as a fire-drift. Fire is introduced at the bottom gallery, and the hot coal face moves up the seam's natural slope as oxidants are fed through one gallery and syngas are withdrawn from the other. The main advantage of this method is that the residual ash and roof material drop down on the void space, which prevents suffocating the gasification process at the coal front [14].
- **LLT gasification method**: mined tunnels or constructed roadways are drilled to connect the injection to the production well. The system consists of a main gasification channel, two auxiliary holes (between the injection and production wells for air and water vapour injection or gas discharge systems), and two auxiliary tunnels. The tunnels are sealed to contain combustible gases. A third tunnel may exist, constructed of bricks and preventing blockage in the main gasification tunnel [11].

Shaftless methods use directional drilling, whereby wells are made at an angle. Preparing a reactor for directional drilling involves creating dedicated in-seam boreholes for oxidant injection and product collection using drilling and completion technology. The approach generally includes drilling inlet and outlet boreholes into a coal seam, increasing the coal permeability between the inlet and outlet boreholes, igniting the coal seam, introducing an oxidant for gasification, and extracting the product gas from the outlet well [14]. This method does not require an underground labour workforce, thus making it much safer for operational personnel. There are two main methods, namely the Linked Vertical Well (LVW) and the Controlled Retractable Injection Point (CRIP).

- **Linked vertical wall (LVW) method**: This is one of the oldest and simplest UCG methods, involving vertical production and injection wells drilled into the coal seam, using the coal's natural pathways to direct oxidant flow. The LVW method has inlet and outlet borehole locations that are static for the system's life. During operation, the coal force migrates, and it is found that system control, performance, and syngas quality are affected negatively as the distance from the coal face to the oxidant injection point increases. Ideally, multiple injection wells should be used, as the coal face moves further from the injection point during gasification, which can reduce syngas quality and system control [14]. This method is most effective with low-rank coals, like lignite, due to their natural permeability, but is less suitable for high-rank coals, such as anthracite [11].
- **Controlled retractable injection point (CRIP) method**: The CRIP method combines conventional and directional drilling techniques to access the coal seam and establish a connection between the injection and production wells. A vertical hole is drilled to a set depth, followed by directional drilling to extend the hole beneath the coal seam, creating an almost horizontal injection well. CRIP offers an approach where the vertical injection well is not moved, but the injection point is moved within the coal seam to fresh coal when necessary. A burner on retractable coiled tubing is used to initiate combustion, and the ignition point can be moved along the injection well if needed [11].

2.5. UCG Products

Underground coal gasification (UCG) produces syngas, a mixture primarily composed of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and trace impurities. The products of in-situ gasification are comparable to those from conventional gasification systems. They can be used directly for electricity generation, converted into methane (synthetic natural gas) for distribution to other gas consumers, or further processed into liquid hydrocarbon fuels [15].

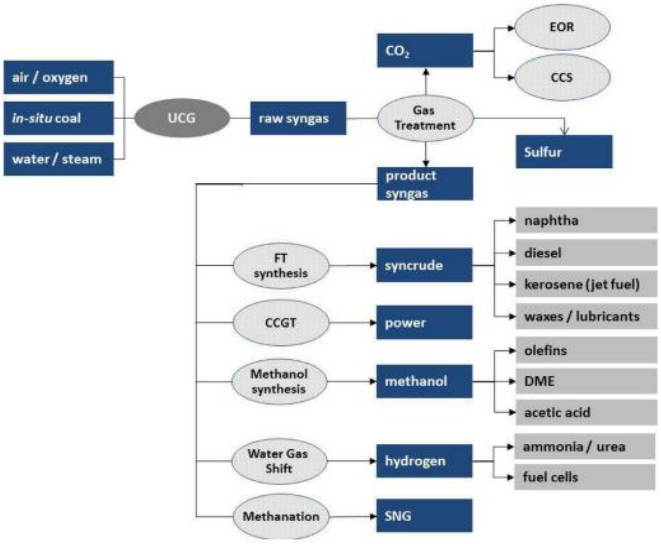


Figure 4. Processes and products of UCG [12].

The hot syngas produced from UCG can be utilized in several ways. It can generate electricity by creating steam to drive a steam turbine, or it can be combusted to produce steam for an electric turbine. Syngas can also be fed directly into fuel cells that can tolerate CO, generating low-voltage electricity that can be stepped up and supplied to the grid. Additionally, after adjusting the H_2 to CO ratio, syngas can be used as a chemical feedstock to produce methanol, hydrogen, ammonia, and other chemical products through the Fischer-Tropsch process. UCG presents a strong case, especially as coal is an obvious source of hydrogen, which could play a crucial role as a near-zero carbon energy carrier in the future [4]. H_2 is valuable for clean energy in fuel cells, ammonia production, and hydrogenation processes. CH_4 is fuel for electricity and heat generation; CO_2 can be captured and stored (CCS) to reduce emissions or used in enhanced oil recovery (EOR). These products make UCG an attractive method for energy and industrial applications.

3. UCG Process

3.1. Key Components of UCG Technology

A UCG operation is a complex process representing a multidisciplinary effort that includes geology, geochemistry, hydrogeology, geomechanics, drilling, pipelines, and chemical, mechanical, and process engineering.

The three critical components of UCG operations that can lead to commercial success:

- Good geological exploration
- Adequate well-completion design
- An advanced process modelling system [9]

3.2. Operational Infrastructure Components

The UCG system consists of three components:

- **Upstream equipment**: comprising compressors for oxidants (air, oxygen), high-pressure water pumps, drilling rigs, structures for injection-production wells, and the piping system.
- **Gasification equipment**: including mixing vessels for air, oxygen, and/or steam and igniters.
- **Downstream equipment**: comprising gas-product pipelines from all production wells to the gas clean-up system, a flaring system of dust cyclones (in case of high ash content in the fuel gas), gas coolers, scrubbers, electro de-tarring equipment, and carbon dioxide (CO_2), sulphur oxide (SO_x: SO_2, SO_3) and nitrogen oxide (NO_x: NO, NO_2) handling and storage devices [9].

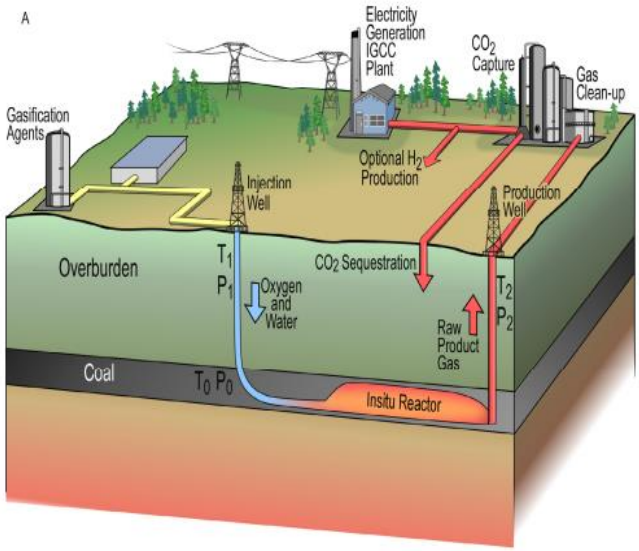


Figure 5. Underground coal gasification system and the input-output surface-operation modules.

3.3. Technical Concept

The simplified underground coal gasification (UCG) process involves drilling two boreholes into a coal seam to create an injection and production system. This system includes surface infrastructure modules, such as gasification and injection equipment, gas cooling and cleaning components, and an underground drilling and linking subsystem. The operation of the injection and clean-up system requires some energy input.

Pressurized oxidants (like air or oxygen-rich gases) are introduced into the coal seam through the injection well. The coal is heated to ignition, and the continuous flow of oxidants sustains the gasification process while the produced syngas is recovered via the production well.

As gasification progresses, a cavity forms underground, expanding laterally and upward toward the coal seam roof. The dissociation of coal gradually moves toward the production well, where the syngas is collected and directed to the surface infrastructure for further processing, similar to conventional surface gasification systems. The syngas typically has a temperature of around 300°C and a pressure higher than atmospheric levels.

The underground cavity, serving as the gasifier, is surrounded by the coal seam's rock layers. The cavity grows through "spalling," where materials from the roof and walls break off. By-products like ash, char, and rock rubble accumulate at the cavity's base, as seen in Figure 6. The cavity's geometry is controlled by adjusting the injection pressure to match the in-situ pressure. Groundwater flowing into the gasifier forms a "steam jacket" around the reactor chamber, minimizing heat loss. Maintaining optimal pressure in the underground gasifier ensures controlled groundwater flow into the cavity, confining the gasification process and preventing leaks or contamination outside the operational area.

Large-scale UCG operations use multiple injection-production modules, where several injection and production well pairs are aligned. These wells are connected to major injection and production pipelines. The high-pressure syngas from different reactors are mixed to ensure a consistent quality of the product gas. If needed, the gas is sent to chemical plants for contaminant removal [9].

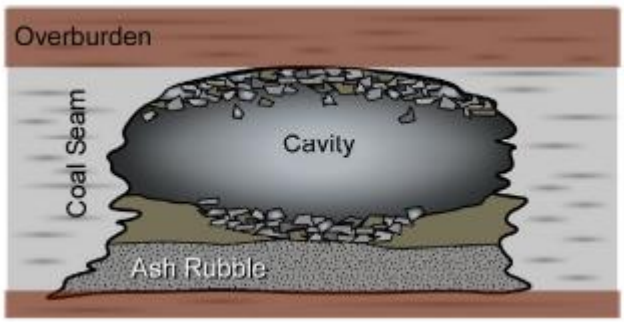


Figure 6. Underground cavity residue [9].

The primary technique for in situ or underground gasification typically involves drilling boreholes to intersect the seam in at least two places and providing a passage for gas through the seam from one intersection to the other. The coal is ignited at the base of one hole, and a gasification agent, such as steam or compressed air, is injected into the seam. The heat from the zone of burning coal causes carbonation and gasification reactions in the coal around it, and the position of the reaction zone is controlled by advancing or withdrawing the end of the injection well. The injection process also drives the products of these reactions towards the other borehole(s), where they are taken off for use [15]. The procedure consists of three steps, explained below.

Step 1: Drilling and Linking

In the first step, as shown in **Error! Reference source not found.**, injection and production wells are drilled from the surface to the coal seam, and a highly permeable path within the coal seam is established between these two wells. Before the gasification step, a linkage path is created between the injector and the producer. Several techniques can be used for linking the wells. These include reverse combustion linking (RCL), forward combustion linking (FCL), hydrofracking, electro-linking, and explosive and in-seam linking.

Different methods of linking

- **Reverse Combustion Linking (RCL):** This method of linking includes the injection of an oxidant into one well and ignition of coal in the other so that combustion propagates towards the source of the oxidant, as shown in Figure 7.

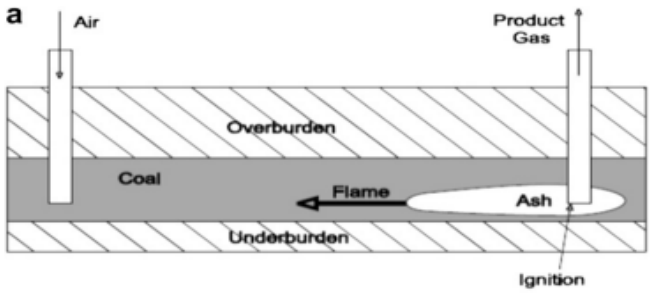


Figure 7. Schematic view of Reverse Combustion Linking (RCL) [1].

- **Forward Combustion Linking (FCL):** In this method, coal is ignited in the injection well, and the fire propagates toward the production well, as shown in Figure 8. During forward gasification, the flame working face gradually moves to the outlet, making the dry distillation zone shorter and shorter. At the time when forward gasification is nearly complete, the reduction zone is also shorter.

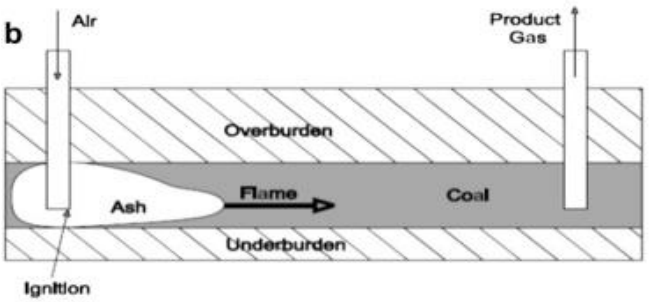


Figure 8. Schematic view of forward combustion linking [1].

The oxidant flow in the injection well is maintained until the fire reaches the bottom of the injection well in the RCL or the production well in the FCL. This outcome is accompanied by a significant drop in the injection pressure,

indicating the creation of a low hydraulic resistance link between the wells, which establishes a low hydraulic resistance path between the two wells [1].

Step 2: Gasification of the Coal Seam

The second step is carried out once a successful link has been established. As seen in **Error! Reference source not found.**, the gasification step starts with igniting the coal and injecting air or air enriched with oxygen. Both permeable bed gasification and natural convection-driven surface gasification will occur. When the gas quality deteriorates, the injection well is burnt, allowing injection further upstream. Gasification occurs when a mixture of air or oxygen and steam is forced into the coal seam through the injection well and reacts chemically with the coal, generating synthesis gas, which is recovered through the production well. The composition of the product gases from UCG can vary substantially depending on the injected oxidant used, operating pressure, and mass and energy balance of the underground reactor. As gasification proceeds, an underground cavity is formed. Water from the surrounding strata will enter the cavity and participate in gasification, leading to a drop in the local water table. At some point, the coal near the injection well will be exhausted, and the first two steps will be repeated to access fresh coal to sustain gas production. In commercial operations, several underground gasifiers are operated simultaneously.

Step 3: Flushing Out the Cavity

Once the gasification operations in a section of the coal seam have finished, the third step is to return the environment to its original state. This is achieved by flushing the cavities with steam and/or water to remove pollutants from seams to prevent them from diffusing into surrounding water aquifers. Over time, the water table will return to a level close to that existing before the start of gasification. This process can be seen in **Error! Reference source not found.**.

3.4. Chemical Reactions

The main chemical processes occurring during coal gasification are drying, pyrolysis, combustion, and gasification of the solid hydrocarbon. These processes occur in all methods of coal gasification, whether conducted in surface gasifiers or in situ. In the drying zone, wet coal is heated and converted into dry coal by removing the moisture attached. Upon further heating of the coal, the pyrolysis reactions begin at temperatures around 350-400°C, and the coal loses its weight, generating volatile matters and the solid known as char (C). Finally, the char reacts with the injected/pyrolysed gases to produce the syngas. The three essential types of char layer reactions that govern the UCG product gas composition are oxidation, reduction, and pyrolysis [13]. The main reactions of the gasification process are summarised in Table 3.

Table 3. Chemicals reactions taking place during underground coal gasification.

Reaction	Reaction Number	Reaction Equation	Heat of reaction (kJ/mol)
Drying	1	$Coal \rightarrow Dry\ coal + H_2O$	+40
Pyrolysis	2	$Dry\ coal \rightarrow Char + volatiles$	0
Coal combustion	3	$C\ (Char) + O_2 \rightarrow CO_2$	+-93.8
CO_2 gasification	4	$C + CO_2 \rightarrow 2CO$	+162.4
Steam gasification	5	$C + H_2O \rightarrow H_2 + CO$	+131.4
Methanation	6	$C + 2H_2 \rightarrow CH_4$	-74.9
Water-gas shift	7	$CO + H_2O \leftrightarrow CO_2 + H_2$	-41
Gas phase oxidations	8	$CO + \frac{1}{2}O_2 \rightarrow CO_2$	-111
	9	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	-242
	10	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	-802

The reactivity of the char to O_2, H_2O, CO_2, and H_2 determines the rates at which the desired products are formed. Reactions 3, 5, and 8 are the main chemical reactions for shallow and deep coal gasification processes. The hydrogasification reaction (6) is favourable at high hydrogen pressures. At low pressure, this reaction is not significant in UCG. Reactions 3-6 occur on the walls of the coal seams (heterogeneous reactions), while reactions 7 and 8 occur at the gaseous stage (homogeneous reactions).

In addition to the above-listed reactions, nitrogen and sulphur reactions are also important. The final product gas consists of hydrogen, carbon monoxide, carbon dioxide, methane, and nitrogen. The composition and heating value of the product gas depend on the thermodynamic conditions of the operation as well as on the composition and temperature of the gasifying agent employed [1].

During in-situ coal combustion, processes such as vaporisation (drying), pyrolysis, and the combustion and gasification of char co-occur. The UCG process is characterized by different zones where gasification reactions occur both in the solid and gaseous phases and at their boundaries. The description of the phenomena at the UCG cavity wall is explained in Figure 9. In the solid phase, the pyrolysis of the drying processes mainly takes place. Along with the migration of the gaseous product of the thermal decomposition through the pores and slots of the solid phase, various homo- and heterogenic reactions occur. The rates of these processes depend primarily on temperature. Heterogeneous reactions occur at the phase boundary within the gasification channel, and their rates are influenced by diffusion and the available reaction surface area. In the oxidation zone, the main products of the reaction between oxygen and carbon are carbon dioxide and carbon monoxide.

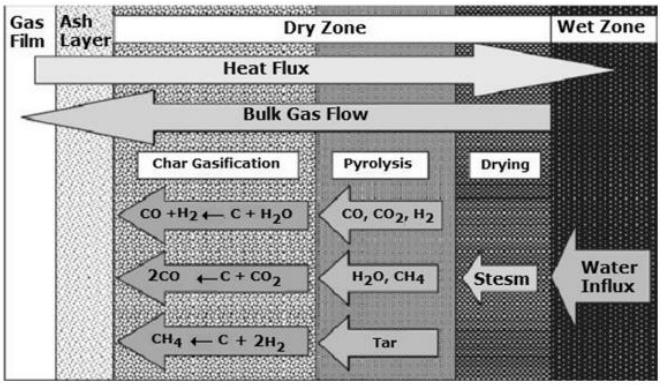


Figure 9. Qualitative description of phenomena at the UCG cavity wall [1].

Based on the critical chemical reactions, temperature, and gas composition, the gasification channel is divided into three zones: the oxidation zone, reduction zone, and dry distillation zone, as illustrated in Figure 10. In the oxidation zone, multi-phase chemical reactions occur between the oxygen in the gasification agent and the carbon in the coal seam, generating heat and causing the coal seam to reach high temperatures, typically between 900-1450°C. The coal becomes incandescent in this zone. The inherent moisture in the coal plays a role in the oxidation process by influencing oxygen transport through the coal pores and participating in chemical reactions during oxidation.

The remaining oxygen is gradually consumed as the air stream enters the reduction zone. In this zone, H_2O(g) and CO_2 are reduced to H_2 and CO due to the high temperatures when they come into contact with the incandescent coal seams. The temperature in this zone ranges from 600-1000°C, and its length is 1.5 to 2 times that of the oxidation zone. Additionally, methanation reactions occur, catalysed by coal ash and metallic oxides. These endothermic reactions cause the temperature to drop, eventually halting the reduction process. After these reactions, the gas stream cools further and moves into the destructive distillation and drying zone, where temperatures range between 200-600°C. In this zone, physical changes occur, especially in coal with high water content, including dewatering, cracking, and contraction at temperatures below 100°C. At temperatures up to 300°C, small amounts of paraffin, hydrocarbons, water, and CO_2 are released. Above 300°C, slow chemical reactions take place, including light polymerization and depolymerization. In the meantime, appropriate amounts of volatile and oil-like liquid are separated, which take a gelatinous state afterwards. When the coal seam temperature reaches 350-550°C, significant amounts of tar oil and combustible gas are produced. Hydrocarbon gases are released at 450-500°C. As the temperature exceeds 550°C, semi-coke solidifies and contracts, producing H_2, CO_2, and CH_4 [1].

As the gas passes through the three reaction zones, it forms a mixture of combustible gases, primarily CO, H_2, and CH_4. The proportions of these gases vary depending on the gasification agent and air injection method used. These zones shift towards the outlet along the airflow direction, allowing the gasification reactions to continue. In the drying zone, surface water in the wet coal vaporizes at temperatures above the saturation point of the seam water at a given pressure, making the coal more porous. As the coal heats further, it enters the pyrolysis stage, losing 40-50% of its dry weight as low molecular weight gases, chemical water, light hydrocarbons, and heavy tars. After the volatile components are released, the remaining solid material, char, becomes more permeable and is combusted and gasified by the injected oxidants and exhaust gases from earlier stages.

Different reactions are favourable at various temperature ranges. Figure 11 shows the equilibrium constants as a function of temperature for some essential reactions in the gasification process. As the equilibrium constants for all the reactions are at unity at approximately 1000K, the temperature becomes a critical factor in determining the shift of chemical equilibria towards the products or reactions by deciding whether it is an endothermic or exothermic reaction. As seen for temperatures above 1000K, the formations of H_2 and CO are favourable since reactions four and five are endothermic. Similarly, the other reactions seem to be favoured at temperatures below 1000K. Reactions involved in UCG are not fundamentally different from the reactions of coal and char in the surface gasifiers. In gasification reaction, the combustion of coal and volatiles provides the necessary heat for endothermic gasification reactions [13].

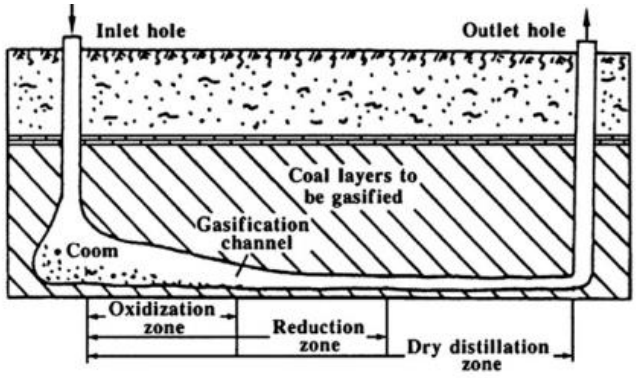


Figure 10. Division of the gasification channel into three zones [1].

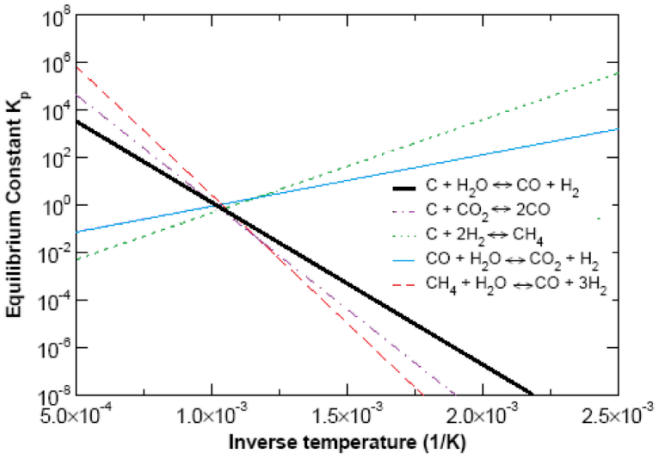


Figure 11. Equilibrium constant Kp as a function of temperature for some reactions in coal gasification [13].

The UCG process is highly exothermic, with temperatures in the burn zone often exceeding 900°C. Even after cooling due to conductive heat loss to surrounding rock and convective heat loss to groundwater, syngas typically exits the production wells between 200°C and 400°C. Around the burn zone, the high buoyancy of hot syngas compared to groundwater can cause large pores to fill with syngas bubbles, which will heat the groundwater and convert it to steam. This creates dynamic interactions between steam and hot groundwater near the burn zone, where the steam mixes with the syngas [13].

3.5. Physical Process

In underground coal gasification, gas movement directly affects the concentration and flow of fluids in the burning zone while limiting the gasification agent's diffusion throughout the gasifier. As a result, it ultimately controls the rate of chemical reactions between gas and solid and the overall burning and gasification process.

High temperatures create a temperature field in the coal and rock layers being gasified. This causes the coal and rock, filled initially with stratification, joints, and fractures, to soften, melt, fuse, and solidify. As a result, their molecular structure is rearranged, leading to changes in their physical structure and appearance. These changes significantly alter the mechanical properties of the coal and rock mass. The high temperatures in the coal body cause the coal seam, filled with layers, joints, and gaps, to soften, melt, fuse, and solidify. This heat reorganises the internal molecular structure, significantly changing the coal seam's surface and physical properties. As a result, the physical and mechanical properties of the coal are no longer constant but vary with temperature. Differences in thermal expansion between coal grains and their anisotropy create new cracks extending and forming a connected network. This enhances the pore connectivity and increases the seepage pressure of the dry distillation gas.

Under non-isothermal conditions, temperature and pressure significantly influence the densities of solid materials and pore water. While the deformation of the solid skeleton is small, it still affects the distribution of the temperature field and groundwater flow in the gasification zone. Therefore, solid particle deformation cannot be ignored and is considered compressible. Pore fluid pressure causes the coal rock to expand and deform, impacting the cracks within the coal skeleton and the opening and closing of pores. Additionally, the fluid in the pores alters the stress-strain relationship of the coal rock, which changes its elastic modulus and compressive strength. The flame front mainly drives the temperature changes in the coal seam. As the temperature increases, the desorption rate of dry distillation gas in the coal accelerates, raising the free gas content and increasing the amount of gas involved in seepage. Conversely, as the temperature rises, the amount of absorbed dry distillation gas in the coal decreases [1].

4. Discussion

4.1. The Importance of UCG in the Context of Energy Production

Coal is a widely available non-renewable resource in most parts of the world. Underground coal gasification (UCG) can turn many poor-quality coal resources into exploitable reserves by delivering energy in the form of synthesis gas, potentially at a low cost. The synthesis gas can be used for electricity generation and the production of fuels, chemicals, and fertilisers using commercially proven technology. Furthermore, the carbon in the synthesis gas not used for downstream products could be easily separated and geo-sequestrated. This could extend the fossil fuel age by providing low-cost energy to developing and developed countries.

UCG technology has also been further positioned as the solution to monetising “unminable” coal. It is also promoted as a technology that provides a means of reducing mining costs by using a non-entry, low labour system, thus making coal extraction safer than traditional methods. UCG also locks away waste materials in underground caverns created during the process and allows for the use of a higher percentage of coal than other mining methods. Additionally, it can use lower-quality coal deposits and help minimize the environmental challenges associated with coal use [16].

4.2. Factors Influencing the UCG Process Performance

The operating conditions that significantly impact cavity growth rate are temperature, water influx, pressure, and gas composition in underground coal gasification. Fundamentally, having low cost, high efficiency, high resource recovery, and reliable operations with low environmental impacts is desirable. While performance should be comprehensively judged by considering efficiency and economic and ecological aspects, this section investigates a more limited set of factors such as operating conditions and coal properties: coal layer thickness, coal reactivity, operating pressure, operating temperature, heat loss, cavity growth, and the type of oxidant used.

4.2.1. Effect of the Thickness of Coal Layers

Most UCG operations have been conducted in more gas-permeable brown coal beds and younger hard coal formations. Typically found at shallow depths of up to 300 meters, these deposits are relatively easy to ignite. However, coals that swell or coke excessively can block the gas flow, disrupting the gasification process. Coal beds should be at least 1 meter thick for better economic viability, as seams thinner than 0.5 meters are generally unsuitable for UCG. During UCG, the burning zone and gases are cooled not only through heat exchange but also by heat loss to the coal seam and surrounding rocks (roof and floor), which affects the stability of the process. Research indicates that in coal seams thinner than 2 meters, heat loss to surrounding rocks significantly reduces the energy content of the produced gas. Increasing the air or oxygen supply for thinner seams can improve gas quality. However, as coal seam thickness decreases or water intake increases, the CO_2 content in the gas also rises [1].

4.2.2. Effect of Coal Reactivity

The chemical reactivity of the coal is significant for UCG. The reported intrinsic reactivities of low-rank coals differ by up to 4 orders of magnitude when extrapolated to typical gasifier operating temperatures. The coal's intrinsic reactivity significantly impacts the gasifier and final product gas distributions. High reactivity favours the production of methane via the char-H_2 reaction. Because this reaction is exothermic, the increased reactivity for this reaction can lead to significant changes in the final product gas calorific value [1].

A controlled set of experiments has been conducted in large coal blocks to establish the influence of coal rank on the likely performance of UCG. From this, sub-bituminous coals have high methane content, moderate to high heating value, and a high gas production rate per unit of coal. Lignite produces syngas with lower heating values and less gas per ton of coal. In the laboratory experiment, bituminous coals produce syngas of a lower heating value similar to that of sub-bituminous coals, with slightly higher gas production per ton of coal. Lignite and sub-bituminous coals are considered suitable for the process due to their volatile matter and moisture content [9]. The rank of the coal, its propensity to spall when heated, and the behaviour of mineral matter upon heating are vital factors in determining the performance of large-scale UCG. Low-rank coals generally shrink and spall upon heating, renewing the sidewall and roof surfaces and establishing a permeable bed of coal and ash through which the injected oxidant can readily flow and penetrate to the surface to gasify the remaining fixed carbon. High-rank coals are less reactive and tend to

swell upon heating, potentially causing problems with the diffusion of volatiles from within the pore structure to reach the surface of the coal. When applying UCG in high-rank coals, a good flow path between the injection and production wells must be established, and the area available for reaction must be maximised. High-rank coals generally have lower volatile contents than low-rank coals, and their low reactivity is more challenging to ignite.

The behaviour of mineral matter during gasification plays a crucial role in the process. If an ash layer forms on the coal, it can significantly hinder the diffusion of oxygen, steam, and carbon dioxide to the carbon, slowing coal conversion to syngas. Similarly, minerals with slagging tendencies can also impede gasification. High levels of sulphur, chlorine, and other contaminants present challenges for the design of surface facilities and the treatment and cleanup of raw syngas. The combination of CO_2 and water at high temperatures and pressures can be highly corrosive, and trace elements like sulphur and chlorine can exacerbate this effect. As a result, material selection for production tubing and surface piping must account for the syngas composition, temperature, and pressure [12].

4.2.3. Effect of Oxidant

The injected oxidant/gasifying agent is usually air, enriched air, steam, or a mixture of steam/oxygen or, water/oxygen, and carbon dioxide. Generally, the type of oxidant affects the calorific value of the syngas produced. When air is used as the gasifying agent, the resulting syngas has a low heating value. This is mainly due to the syngas dilution by the nitrogen contained in the air. However, using steam or a combination of steam and oxygen produces syngas with a medium calorific value. Adding steam shifts the carbon-oxygen system balance to a carbon-oxygen-steam system during combustion. Oxygen-steam gasification utilises excess heat to enhance energy efficiency and increase gas production per ton of coal. The changing relationships between gas compositions and steam/oxygen ratios are illustrated in Figure 12.

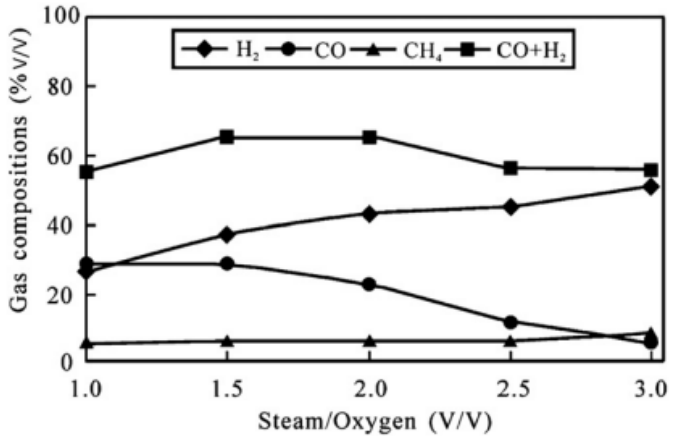


Figure 12. Gas composition variation with steam/oxygen [1].

In pure-oxygen underground coal gasification, water from the coal seams or leach water from the roof can generate water gas. However, since water evaporation consumes heat and steam volume cannot be precisely controlled, gas compositions often fluctuate widely. To stabilise the gasification process, it is necessary to adjust the oxygen supply accordingly. As shown in Figure 12, as the steam-to-oxygen ratio increases, the volume of steam rises, leading to an increase in hydrogen (H_2) content in the gas, a decrease in carbon monoxide (CO), and a slight increase in methane (CH_4).

When air is injected into a gasification channel at a low speed, the flame moves toward the injection point. However, if the airflow rate increases, the cavity expands downstream. Flame propagation is faster with oxygen than with air, as oxygen-fed flames burn hotter and react more quickly. At high temperatures, with high activation energy and strong airflow, the channel surface forms two zones: a cold zone, where the temperature is too low to trigger reactions, and a hot zone, where any oxygen present reacts immediately. Due to the high activation energy, these zones are separated by a small distance. The overall reaction rate is dictated by oxygen diffusion to the hot zone, while the oxygen concentration on the hot walls is essentially zero. In these conditions, the turbulent flame is governed entirely by diffusion, meaning the injection rate no longer influences the flame's position. The combustion of coal starts with devolatilization reactions at lower temperatures, which the airflow can cool. If these reactions significantly impact the initiation of oxidation or the overall energy balance, the flame's position can be controlled by adjusting the airspeed.

All other factors being equal, increases in flow rate and operation time lead to a steady growth in both the cavity's dimensions and its volume. However, increasing the distance between the injection and production wells reduces the overall cavity volume, as the cavity's forward growth rate slows significantly [1].

4.2.4. Effect of Pressure

Pressure is known to have a positive effect on coal gasification performance. At near-atmospheric pressure, the calorific value of the gas is low due to kinetic limitations in the gasification reactions. Adjusting operating pressure can significantly enhance the underground gasification process. Under cyclic pressure changes, heat loss is notably reduced while heat efficiency, gasification efficiency, and the calorific value of the gas increase substantially. A gasifier with a long channel and large cross-section improves combustion and gasification conditions, greatly enhancing the quality of the product gas and stabilizing gas production. Therefore, a large-scale underground gasifier is essential for industrial production [1].

4.2.5. Effect of Heat Loss

Estimating heat losses from underground coal gasification is difficult. If the cavity remains entirely within the coal seam, heat losses to the surrounding strata are likely minimal and can often be disregarded. However, irreversible heat losses to the surrounding areas increase as the overburden becomes exposed. This heat loss is hard to predict, especially if the overburden undergoes spalling, since some of the heat used to reach cavity temperatures may be recovered by preheating the injected gas [1].

4.2.6. Effect of Temperature

The UCG process operates on a self-regulating heat balance. The heat generated by coal combustion helps establish the ideal temperature field within the underground gasifier, facilitating gasification reactions and producing syngas. Temperature plays a critical role in maintaining stable, continuous production. The gasification agent, modes of gasification, and cavity changes influence the temperature variation patterns in the gasifier. Under pure oxygen gasification, the average temperature increase in the coal seam is around 4.15°C per hour. During oxygen-steam forward gasification, high temperatures, up to 1300°C in the oxidation zone, are concentrated in the loosened areas caused by thermal explosions. In comparison, backward gasification generally results in lower average temperatures, which decreases CO levels while increasing H_2, CH_4, and CO_2 concentrations.

In the thermal-explosion gasification method using pure oxygen, the temperature of gasified coal seams rises at an average rate of about 4.15°C per hour. During the oxygen-steam forward gasification phase, the temperature field is primarily concentrated around loosening zones caused by thermal explosions, with the highest temperature in the oxidation zone reaching approximately 1300°C. Research indicates that forward oxygen-steam gasification with moving points can significantly enhance the temperature conditions within the gasifier. In backward oxygen-steam gasification, as time progresses, the temperature of the coal seams gradually increases and stabilizes, eventually becoming similar to that of forward gasification. Thus, backward gasification can create new temperature conditions, improving the gasification efficiency of the coal seams.

During coal gasification, temperature changes in the coal seam are primarily driven by heat transfer from the flame working face, acting as the primary heat source. In underground coal gasification, the temperature of the surrounding coal seams increases due to heat conduction. As the coal surface is heated by hot gas or nearby burning coal, the temperature spreads inward toward the coal grains and deeper into the seam. This process triggers thermal effects such as absorption, desorption, and the movement of dry distillation gases stored within the coal seam [1].

4.2.7. Cavity Growth

As the coal gasification reaction progresses, an underground cavity composed of coal, char, ash, rubble, and void space forms. The size of this cavity significantly affects UCG's economic and environmental outcomes. Lateral dimensions determine resource recovery by influencing module spacing, while overall dimensions impact hydrology and the risk of subsidence in the overburden. The shape and size of the gasification channel during UCG are critical to ensuring the safety and stability of the upper geological layers. As the cavity expands upward, it eventually reaches the interface between the coal seam and the overburden, where interactions between the gas mixture and the overburden influence further development.

At the beginning of UCG, an exothermic coal combustion reaction is needed to create an initial underground cavity. During this stage, cavity growth is not limited by the roof. Once a stable temperature is established, steam is introduced for coal gasification, producing combustible gases. The cavity's shape and growth rate impact fundamental phenomena, including gas flow patterns, reaction kinetics, and temperature distribution. The cavity size at any

time is tied to coal consumption, while its shape reflects the irregular flow patterns within the cavity.

The cavity is generally symmetrical around the injection well. Its backward growth (behind the injection well) is smaller than its height and width at the injection point. In contrast, the forward length (from the injection well to the forward tip of the cavity dome) is more prominent, as the convective flow of reactant gases in that direction promotes additional growth. The final cavity dome is nearly hemispherical, though connected to a long outflow channel.

As coal consumption and thermomechanical spalling increase, the cavity volume expands irregularly in all directions. The flow pattern within the UCG cavity is complex due to concurrent processes like heat transfer, water intrusion from aquifers, chemical reactions, and spalling. Cavity volume is directly proportional to coal consumption, while the shape depends on growth rates in four key directions. The coal consumption rate drives overall cavity growth, while gas flow and gas effects like spalling influence the shape and growth direction.

Based on coal's physical and chemical properties and the coal seams' geological conditions, two gasification channels can form within the gasification panel: a free-flowing channel without a solid phase and a porous, loose channel with a percolation pattern. In the longitudinal (radial) direction, the free-flowing channel can be divided into three zones: free-flowing, reaction, and coal seam. Gas moves through these zones, continuously exchanging heat with the channel walls, consuming or producing various compounds. Simultaneously, homogeneous reactions take place within the gas phases.

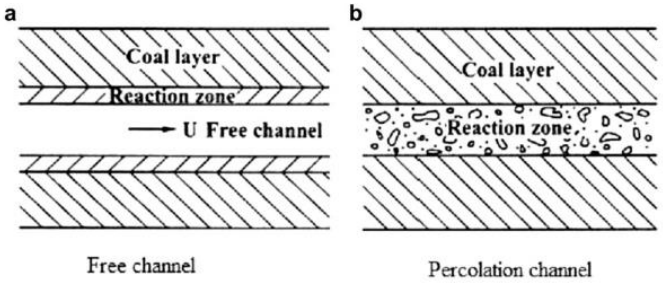


Figure 13. Gasification channels in coal seams [1].

In the reaction zone, key processes like oxidation, reduction, and pyrolysis of coal occur. Heat transfer to the gas phase and the consumption and production of compounds serve as boundary conditions for the gas flow. In the coal seam zone, part of the heat from the reaction zone is lost to the coal seam, mainly through conduction, which leads to the drying and distillation of the coal.

Cavity growth significantly affects coal resource recovery, energy efficiency, and economic viability. It also relates to critical design considerations, such as preventing surface subsidence and groundwater contamination. Since installing injection and production wells is costly, maximizing the volume of coal gasified between each well pair is essential. As gasification progresses, a cavity forms and grows laterally, aided by the roof's collapse. Roof collapse is crucial for expanding the gasifier laterally. However, if the roof is too strong or consists of poorly consolidated, blocky material, some fluid reactants may bypass the coal, leading to a sharp decline in reactor efficiency. Generally, deeper gasifiers offer more favourable conditions for development, with a reduced risk of bypass issues, except in cases of extremely strong roof conditions [1].

4.3. Optimisation of the UCG Process

Underground coal gasification (UCG) cannot be controlled precisely as surface gasification since the coal feedstock cannot be processed. However, UCG operations can still maintain stability and flexibility. Input flow rates directly impact production flow, with minimal effect on the product gas quality. Power output from the gasifier can be rapidly adjusted by increasing or decreasing the oxygen flow rate. While greater depth and pressure are not required for high-quality gas production, they allow for higher mass flows, improving energy transmission efficiency to the surface.

A UCG system's energy output depends on the flow rate of the produced gas and its calorific value. Typically, the volume of the product gas is about four times the injection flow, with the limiting factor being the dynamic resistance of the production well. The mass flow capacity of a well is proportional to input pressure, and increasing the well depth enhances gas density and pressure, resulting in a mass flow gain that exceeds friction losses due to the extended borehole. Increasing the diameter of production tubing or adding more production wells can also raise the limiting flow rate.

Continuous monitoring and updates on process conditions are essential as gasification progresses. While ideal temperatures for surface gasification are around 1000°C, achieving these temperatures in UCG can be challenging due to uncontrolled water influx and irregular reactant gas flow patterns [1].

4.4. Environmental Impact

UCG offers both economic and environmental benefits. Since most of the process occurs underground, large tracts of land remain available for use, reducing surface disruption. Additionally, UCG allows for underground ash disposal, minimizing surface waste and lowering occupational health risks as no personnel are needed underground. The process also generates less atmospheric pollution and uses less water than ex-situ gasification, requiring a higher steam-to-air ratio to prevent slagging. The overburden material acts as natural insulation, resulting in higher thermal efficiency for UCG than surface gasification methods.

Compared to conventional coal mining methods, UCG is often preferred because it eliminates the need for mining, cleaning, transport, and storage, which incurs capital and operating costs. These steps also generate solid, liquid, and gaseous residues that must be treated before disposal. UCG streamlines these processes into a single operation that is more environmentally friendly and cost-effective [11].

However, UCG presents some environmental challenges. Carbon dioxide emissions remain a significant concern since the process still relies on fossil fuels as feedstock. Additionally, UCG's operational considerations are closely tied to environmental factors. Unlike conventional surface coal gasification plants, where the reactor environment is fully engineered and controlled, the performance of in situ gasification is heavily influenced by the geological and hydrological conditions of the site. Therefore, the design and operation of any UCG system must be based on a thorough understanding of the gasification site. The accompanying illustrates how a UCG operation could affect the air, surface soils, surface water, underground rock formations, and groundwater. The following sections will examine potential surface and subsurface impacts and greenhouse gas emissions.

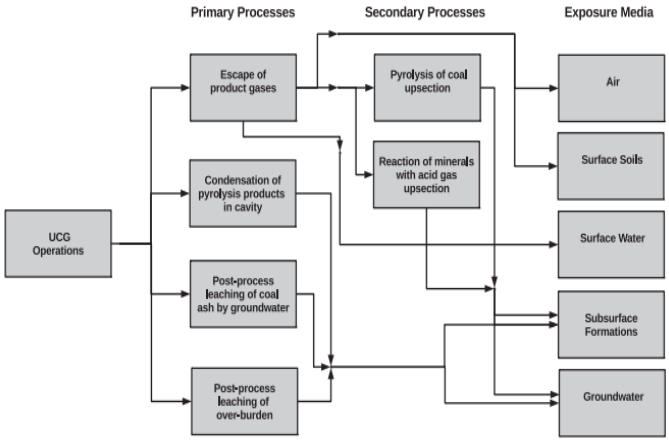


Figure 14. Potential environmental impacts of UCG [12].

4.4.1. Surface Impacts

UCG operations can, in principle, lead to the escape of product gases into the air and surface soils and the deformations and subsidence of the surface topography. The most likely way for product gases to reach the surface air or shallow soils is via the wells (injection, production, monitoring) drilled from the surface. Therefore, the design of the casing and cement of the wells is fundamental. Operational procedures and safety systems must also be implemented to prevent well blowouts.

Subsidence of the surface ground due to UCG is another potential impact. It depends heavily on the formation depth and thickness, the strength of formation materials, and the width of the zones of coal conversion. As the void within the reactor space grows, surface material moves downward as the coal bed does not support it. Though the magnitude of subsidence depends on the type of rocks, depth of the bed, and geometry of the void, it should be noted that this is common for UCG or conventional mining in general [11]. Shallow coal seams experience significant subsidence. Projects can develop large surface craters. UCG projects at deeper coal seams with strong overburden materials experienced negligible or no subsidence. Subsidence risk can be minimised through careful site investigation selection and using geomechanical models to design the gasifier field layout properly [12].

4.4.2. Groundwater Pollution

A major concern regarding groundwater pollution during UCG operations arises from the release of organic compounds such as BTEX, phenols, and polyaromatic hydrocarbons (PAHs) during coal pyrolysis and gasification, as well as the release of heavy metals and leaching of inorganic materials from residual char and ash after gasification ceases. Key inorganic contaminants include a variety of ionic species like sodium, calcium, sulphate, bicarbonate, chlorine, ammonia, fluoride, and bromide, as well as metals, arsenic, and boron.

The extent and concentration of groundwater contamination depend primarily on the groundwater flow velocity, dispersion, and the reactions and adsorption behaviour of the contaminants. Managing the risk of groundwater pollution near UCG operations should be a primary focus during site selection, design, and operational phases. Many organic pollutants, such as BTEX, phenols, and PAHs, are denser than syngas and tend to condense into the liquid phase at lower temperatures, meaning they typically remain close to the UCG cavity. Additionally, these compounds have low solubility in water, limiting their spread [12].

The contamination of surrounding groundwater through outward gas flow from the reactor seam can be managed by operating the pressures below the hydrostatic pressure. This also helps by using the groundwater as an additional oxidant. Ideally, UCG sites should be as far away from groundwater sources as possible, though if this is not achievable, regular water testing and treatment should form part of operations [11].

4.4.3. Groundwater Depletion

Most UCG demonstration projects have observed a drop in formation pressure during operations. This occurs because the operating pressure of UCG is intentionally kept below the surrounding formation pressure, creating a driving force for water to flow into the gasification zone. The coal gasification process consumes water to produce CO and H_2 through the steam gasification reaction. The pressure drawdown during operations indicates that UCG surface facilities must be designed to handle a range of pressures.

Targeting deeper coal seams for future UCG projects is advantageous because the relative pressure drawdown will be smaller as a percentage of the baseline pressure, simplifying the design of surface facilities. Freshwater or treated produced water could be injected back into the formation around the UCG gasifiers to mitigate groundwater depletion. The effectiveness of this strategy would depend on various factors, including the permeability of the coal and the surrounding overburden layers [12].

4.4.4. Greenhouse Gas Emissions

The carbon emissions from energy technologies are of significant social concern. It is widely recognized that global carbon emissions must decrease to keep global warming within 1.5-2°C above pre-industrial levels. Although coal is abundant and relatively inexpensive, it is a high-carbon fuel, emitting considerable amounts of CO_2 for each unit of energy generated when burned [12].

The combustion of coal releases CO_2, and UCG is no exception. However, like other gasification methods, UCG offers enhanced potential for carbon capture and storage (CCS). The syngas produced during UCG can be processed to separate CO_2, which can then be sequestered or repurposed.

Long-term storage of CO_2 in geological formations is being extensively researched. Key targets for carbon storage include deep saline aquifers, depleted gas fields, active oil fields, unminable coal seams, and depleted oil or gas fields—many of which are often located near UCG-eligible coal seams. This proximity makes underground CO_2 storage a viable option at UCG sites. The economics of carbon capture and the availability of storage targets make UCG-CCS an appealing approach to carbon management. In a UCG-CCS scenario, syngas generated from UCG would be extracted, the by-products separated, and the CO_2 returned to nearby geological formations for storage.

There has been some consideration of using the cavity formed in the coal seam by UCG for CO_2 storage. This approach benefits from pre-existing boreholes and the large cavity volume, but also presents challenges. The integrity of the cavity may be compromised due to cracking and collapse caused by the UCG process. Additionally, CO_2 can interact with water to form carbonic acid and with coal, char, and ash to form sulfuric acid. These acids, along with CO_2, could potentially migrate out of the cavity, increasing the risk of leaching metals and other harmful chemicals into groundwater. Volatile organic compounds (VOCs), such as benzene, might dissolve into the CO_2 and be carried out of the reservoir, possibly travelling upward through the crust. These processes could raise the risk of groundwater contamination, even for deep UCG operations [3].

4.5. Advantages and Disadvantages of UCG

4.5.1. Advantages of UCG

The three major criteria to be considered when evaluating the UCG process include accessibility to an otherwise uneconomic coal resource, process efficiency (power generation and chemical feedstock) vs operational cost and control of the environmental impact.

The UCG process offers accessibility to uneconomic coal resources as it makes deep or difficult-to-access coal seams into usable energy assets. Only 1/6 to 1/8 of the world's coal reserves are economically mineable [3]. It can be applied to multiple-layered seams, saving part of the operational cost. In a large exploration area, concurrent activities, such as oil and gas exploration, coal mining, and UCG, can be conducted at different target depths [9].

The efficiency of the UCG process is enhanced by its lower operational costs, as it eliminates the need for traditional coal mining, handling, and transportation. Additionally, there is no need for ash or slag removal, as inert materials largely remain in the underground cavities. UCG can also be integrated with existing power plants, allowing the produced syngas to be directly utilized for electricity generation. The efficiency of the power-generating process also means reduced rates of greenhouse emissions per unit of net power generated and half the quantity of water required compared to conventional coal-fired power plants. The syngas is produced under pressure and at moderately high temperatures and easily lend themselves to CO2 removal by various methods, with low energy penalty and relatively low cost. The process also eliminates the need for mining, the dangers to miners, and the environmental degradation associated with it.

The environmental efficiency of UCG is considered less than surficial gasification or coal-fired power generation due to reduced emissions, no appreciable change in the landscape, and no surface disposal of ash and coal tailings. Some of the potential UCG sites are also potential CO_2 sequestration sites. Captured CO_2 can be stored in the underground cavities created by coal removal during UCG operations. The energy penalty and relative cost of CO_2 compression and injection are comparatively low. Also, the CO_2 can be stored in deep saline aquifers and deeper coal seams or used for oil, natural gas, and CBM-enhanced recovery. As coal processing is kept underground, surface and air emissions of sulphur, nitrous oxides, and mercury are dramatically reduced [9].

Compared to surface gasification, UCG requires much smaller gas cleanup equipment because both the tar and ash content of UCG-based syngas is substantially lower than that obtained from a surface gasifier.

4.5.2. Disadvantages of UCG

The disadvantages and risk factors associated with the UCG process are related to technological, economic, and environmental issues. UCG, like any other conventional process, depends on the rate of technological advancement. Any technological advance in this field or a related field is sooner or later reflected in enhanced syngas production with reduced emissions relative to conventional coal combustion and at lower overall cost. The greater the economic interest, the more the UCG's technological progress accelerated.

The UCG technological and environmental disadvantages and risk factors can be summarised as cavity collapse, roof subsidence, and groundwater contamination. The performance of the UCG operation depends on several factors that can be improved by more comprehensive combustion/gasification simulation models and monitoring processes [9].

The cavity UCG creates may cause significant deformation in the remaining coal and surrounding rocks. Heating, quenching, water flux, and potential roof and wall collapse may seriously compromise the integrity of the cavity. In general, the sides of the cavity move inward, the floor upward, and the roof downward (subsidence). The magnitude and form of subsidence are functions of many factors, including seam depth (thickness and overburden), effective rock stiffness, and yield strength.

UCG operations are inherently more challenging to control than surface gasifiers, posing risks due to the high temperatures and pressures in the cavity. Geological or hydrological characteristics of specific coal seams can heighten environmental risks to unacceptable levels. In full-scale UCG, the larger reaction zone may lead to a significant groundwater depression, causing water to flow into, rather than away from, the combustion zone. The high temperatures and pressures involved in UCG result in the production and transportation of toxic organic compounds from the burn cavity, regardless of the coal type used. Deeper UCG sites require even higher pressures and temperatures to sustain the burn zone, increasing the risk of contaminants flowing outward to regional groundwater. Additionally, using UCG sites for carbon capture, utilization, and storage (CCUS) could increase contaminant mobility, as organic compounds tend to be highly soluble in CO_2, and metals

become more mobile under acidic conditions. However, controlling groundwater flow into the cavity rather than away from it could significantly reduce the movement of soluble contaminants [4].

Table 4. Additional advantages and disadvantages of UCG [1].

Advantages	Disadvantages
Exploits unmineable coals, increasing resource availability	Shallow seams are unsuitable for gasification due to gas losses, surface breakthroughs, and groundwater contamination.
Ideal for lignite, sub-bituminous, and non-swelling bituminous coals	Low reactor pressure in shallow seams results in reduced gas quality and high heat losses
Deeper coals yield higher pressure, methane content, and heat value	Thin seams are uneconomical unless in multi-seam environments
UCG offers higher thermal efficiency than surface gasification	Well-pair installation is costly, so maximising coal volume between wells is critical
CRIP concept improves oxygen efficiency and minimizes subsidence	Surrounding rock in UCG is affected by high temperatures, altering mechanical properties
Lower capital and operational costs, fewer safety risks, and reduced surface damage	High temperatures cause stress displacement in the surrounding rock.
Less water used; the UCG process utilised seam water; less ash and gas cleanup required.	
Minimal surface disturbance and easier pollutant handling	
Less greenhouse gas emissions; Co_2 sequestration potential in UCG zones	

4.6. Economic and Environmental Benefits of UCG

Underground coal gasification offers several economic benefits. They include lower capital and operating costs and greater flexibility in accessing coal resources. UCG enables the exploitation of larger coal reserves that may be inaccessible or uneconomical through traditional mining methods. The process minimised surface disturbances, reducing fugitive dust and visual impacts while lowering water consumption and the risk of surface water pollution. Additionally, UCG reduces methane emissions and eliminates the need to handle dirt, wash coal, and manage fines and ash disposal at mine and power station sites. The absence of coal transport, stocking, and the associated infrastructure results in smaller surface footprints at power stations. Furthermore, UCG reduces liabilities related to mine water recovery and surface hazards, enhancing the process's economic and environmental sustainability. This makes UCG strategically valuable for power generation and chemical industries [1].

5. Conclusions

This paper has provided a comprehensive review of underground coal gasification, focusing on the historical background and evolution of UCG, the geological requirements and the different UCG methods. Emphasis has been placed on the chemical and physical processes and the factors that affect the process. The environmental impact, economic and environmental benefits of UCG and advantages and disadvantages have also been discussed.

- Although UCG is not a new concept, the process has yet to be implemented at large despite many decades of development. The success of UCG depends on careful site selection, which accounts for geological and hydrological factors. Optimal coal properties, such as depth, thickness, and permeability, ensure efficient gasification and minimal environmental impact. With proper geological exploration and control of combustion processes, UCG offers a viable, low-impact method for utilizing coal resources.
- UCG offers a versatile and efficient way to extract energy from coal deposits through in situ gasification. The process involves various methods, including shaft and shaftless techniques, to ignite and gasify coal seams.
- UCG's main product, syngas, can be utilised for electricity generation, chemical production, or as a fuel, offering a wide range of industrial applications. Additionally, UCG has the potential to produce hydrogen, which could play a vital role in future clean energy systems while also reducing environmental impacts through carbon capture and storage.
- The process offers a viable method for harnessing energy from coal seams that are otherwise difficult to mine. By utilising a system of injection and production wells, UCG enables coal gasification in situ, converting it into syngas through a series of chemical reactions. The process depends highly on geological factors, well-completion designs, and process modelling.
- UCG represents a significant advancement in using coal as a viable energy source, particularly in accessing unmineable and lower-quality coal reserves. By optimising various factors influencing UCG performance- such as coal layer thickness, coal reactivity, oxidant type, operating pressure, and temperature- industry stakeholders can enhance the efficiency and reliability of the process.
- Ultimately, UCG offers a pathway for sustainable energy production. It enables developed and developing nations to harness coal resources while contributing to a cleaner energy landscape through potential carbon capture and storage solutions. As technological advancements continue, UCG has the potential to play a pivotal role in the transition to a more sustainable energy future.
- UCG is a promising advancement in energy production, combining economic advantages with environmental benefits. By enabling the extraction of previously unmineable coal resources, UCG reduces operational costs and minimizes surface disruption, which lowers risks associated with traditional mining methods.
- While it presents significant opportunities for cleaner energy production and carbon management through potential carbon capture and storage, UCG has challenges. Concerns regarding groundwater contamination, subsidence, and greenhouse gas emissions necessitate thorough site evaluation and operational oversight. Nonetheless, with careful management and technological advancements, UCG can contribute significantly to sustainable energy solutions, making it a valuable option in transitioning toward cleaner energy sources.

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Credit authorship Contribution Statement

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Conflicts of Interest

The authors declare that they do not have any personal or financial conflicts of interest.

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