UNDERGROUND COAL GASIFICATION: FROM CONCEPT TO COMMERCIAL APPLICATION

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ABSTRACT

Ensuring a reliable and sustainable energy supply represents one of the most critical environmental, economic and societal challenges of the 21st century. Despite the accelerated transition to renewable energy sources, fossil fuels- especially coal are expected to remain a significant energy component in the foreseeable future. Researches indicates a continued increase in coal demand, underscoring the necessity for more efficient, economically viable, and environmentally acceptable utilization technologies. Underground coal gasification has emerged as a promising in situ technology that enables the exploitation of deep, thin, or otherwise uneconomic coal seams that are not accessible through conventional mining technologies.

A lot of researches point to the potential advantages of UCG over traditional coal mining technologies, including higher recovery rates, reduced land degradation, improved economic performance, and potentially lower greenhouse gas emissions, especially when it is integrated with carbon capture and storage (CCS) technologies. This paper provides a comprehensive overview of the current state of UCG development globally, where we can critically analyze the technological maturity, its economic viability and environmental implications

Keywords: underground coal gasification, clean coal technology, CCS, ecology, coal

INTRODUSTION

Despite the global transition toward renewable energy sources, fossil fuels—particularly coal—are expected to continue playing an important role in the global energy mix over the coming decades. A significant proportion of the world's coal reserves are located at great depths, where conventional mining is technically challenging and economically unfeasible.

Coal extraction at depths exceeding 500 m is economically viable only under favorable geological conditions, while coal deposits located beneath the seabed or within complex geological structures are virtually inaccessible using conventional mining methods. It is estimated that more than 80% of global coal reserves are located under such conditions.

Global coal demand is projected to increase by approximately 20% by 2035, further emphasizing the need for more efficient and environmentally sustainable technologies for coal utilization. At the same time, coal remains one of the major sources of environmental pollution and contributes significantly to increasing atmospheric carbon dioxide (CO_2) concentrations. In this context, the application of Clean Coal Technologies (CCT) represents a key approach to balancing energy demand with environmental protection requirements.

Underground Coal Gasification (UCG), also referred to as *in-situ* coal gasification, is an alternative technology that enables the utilization of otherwise inaccessible coal resources by converting them directly underground into gaseous or liquid fuels. The concept of underground coal gasification is not new. As early as 1862, the renowned chemist Dmitri Mendeleev proposed that, in the future, coal would be burned underground and the resulting gas transported to the surface through pipelines. In 1867, the German scientist William Siemens was the first to publicly present the concept of underground coal combustion before the Society of Chemical Industry in London.

The basic principle of UCG involves drilling several boreholes into the coal seam. After ignition of the coal, one borehole is used to inject oxidizing agents such as air, oxygen, or steam into the gasification zone. The produced synthesis gas (syngas) is then transported to the surface through a second borehole, commonly referred to as the production well.

Table 1 Estimated coal stocks suitable for UCG [1]

Region/State	Coal supplies for underground coal gasification [billion tons]	Amount of gas from underground gasification of stocks [trillion m^3]	Current supplies of natural gas [trillion m^3]
USA	138,1	41,4	5,5
Europe (without Russia)	130,1	21,8	6,0
Russian Federation	87,9	26,3	47,8
China	64,1	19,2	2,4
India	51,8	15,5	1,1
South Africa	48,7	8,2	0,0
Australia	44,0	13,2	2,5
TOTAL	564,7	145,6	65,2

TECHNOLOGY OF UNDERGROUND COAL GASIFICATION

The Underground Coal Gasification (UCG) process consists of four main stages: drilling of boreholes, establishing a connection between the boreholes, initiating the combustion process (ignition), and coal gasification [2].

In its simplest configuration, a UCG system comprises two boreholes: an injection well through which gasification agents (air, oxygen, and/or steam) are injected into the coal seam, and a production well through which the generated synthesis gas (syngas) is extracted. With the advancement of UCG technology, three well configurations have become the most widely applied:

- Linked Vertical Wells (LVW);
- Controlled Retracting Injection Point (CRIP);
- Steeply Dipping Seams (SDS).

In the Linked Vertical Wells (LVW) configuration, the injection and production wells are drilled at a predetermined distance apart, both reaching the target coal seam. A permeable linkage is then established between the two wells, providing a continuous flow path for gases and enabling the uninterrupted gasification process.

The next stage is ignition, during which the coal seam is heated using a combustible gas–oxygen mixture activated by an appropriate ignition source. The duration of this stage depends on the geological and physicochemical characteristics of the coal seam, as well as on the selected operating parameters.

Once a stable combustion reaction has been established, the gasification stage begins. Air or oxygen, usually combined with steam, is continuously injected into the coal seam. Under high-temperature conditions, the coal is converted into synthesis gas (syngas), consisting primarily of hydrogen (H_2), carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), and smaller quantities of other gaseous compounds. The produced syngas is transported to the surface through the production well and can subsequently be utilized for electricity generation, heat production, hydrogen production, synthetic fuels, or as a feedstock for the chemical industry.

As the gasification process progresses, the coal is gradually consumed, while the mineral residue (ash) accumulates at the bottom of the gasified zone, forming an underground void known as the **gasification cavity**. When this cavity expands to the production well, the contact between the injected gasification agents and the remaining coal decreases significantly, resulting in a reduction in both the quality and calorific value of the produced syngas. To maintain efficient gasification, the injection point is relocated to a new section of the coal seam, thereby extending the operational life of the gasifier and improving overall resource recovery.

After completion of the gasification process, the cavity is typically flushed with steam and/or water to reduce the concentration of residual contaminants within the coal seam. This post-gasification treatment helps minimize the migration of pollutants into surrounding groundwater aquifers and represents an important measure for environmental protection.

Chemical reactions in UCG

The ICG process occurs in three different zones: drying, pyrolysis and combustion and gasification of solid char.

In the drying zone, wet coal is heated and converted into dry coal by removing moisture attached to it. Upon further heating of coal, the pyrolysis reactions begin at temperatures around 350-400 °C, and coal loses its weight, generating volatile matters and the solid known as char [3].

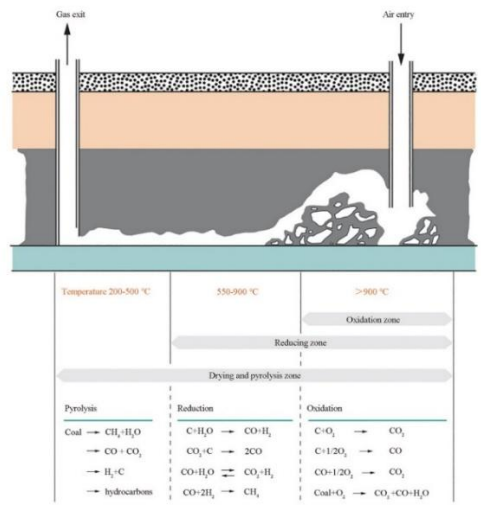


Fig. 1. Schematic of the significant events in underground coal gasification [4]

Finally, the char reacts with the injected/pyrolyzed gases to produce the syngas. The three essential types of char layer reactions which govern the UCG product gas composition are:

- oxidation;
- reduction;
- pyrolysis.

METHODOLOGY

This study was conducted using a comprehensive review methodology aimed at evaluating the historical development, technological progress, environmental performance, and commercial potential of underground coal gasification (UCG). The research is based on the systematic analysis of published scientific literature, technical reports, industrial case studies, and international energy publications. A qualitative comparative approach was adopted to identify the key technological advancements, operational experiences, economic performance, and environmental challenges associated with UCG implementation in different countries.

The review focuses on the evolution of UCG from early experimental projects to recent commercial-scale developments, providing an integrated assessment of its current technological maturity and future prospects.

The analysis included peer-reviewed journal articles indexed in Scopus and Web of Science databases, conference proceedings, books, technical reports, and publications issued by international organizations such as the International Energy Agency (IEA), United Nations Economic Commission for Europe (UNECE), and the International Panel on Climate Change (IPCC). Industrial reports published by companies involved in UCG development were also considered where relevant.

The literature covered publications from the early experimental period of underground coal gasification to the most recent developments published untill 2025.

The reviewed publications were selected according to the following criteria:

- relevance to underground coal gasification technology;
- availability of technical or operational data;
- description of pilot-scale or commercial UCG projects;
- information regarding geological conditions, gasification technologies, environmental impacts, and economic performance;
- publication in recognized scientific journals or by internationally recognized organizations.

Studies with insufficient technical information or duplicated data were excluded from the analysis.

A comparative analysis was performed to evaluate the development of underground coal gasification projects in different countries, including the former Soviet Union, the United States, Europe, Australia, China, and South Africa.

The comparison was based on the following evaluation parameters:

- geological conditions;
- coal seam depth;
- seam thickness;
- gasification agent;
- drilling technology;
- syngas composition;
- heating value;
- coal recovery;
- process efficiency;
- environmental performance;
- commercial applicability.

GLOBAL TECHNOLOGICAL DEVELOPMENT

Development of Underground Coal Gasification (UCG) Technology in USSR

The Soviet Union was the pioneer in the development of Underground Coal Gasification (UCG), conducting the world's first experimental UCG trials in 1933. Three initial experiments were carried out in the Moscow Basin, including two in lignite seams and one in anthracite, while two additional experiments were performed in the Donets Basin. At the Donbas coalfield, preparatory work began at the Gorlovskaya experimental station in 1933, and in 1935 the world's first successful underground coal gasification process was achieved.

The earliest experiments replicated the principles of conventional surface gasification technology by constructing underground mine workings and creating artificial fractures using explosives. The Gorlovskaya station represents the first stage in the development of UCG technology, which focused primarily on testing different gasification techniques and operational methods. During the second stage of development, research shifted towards achieving reliable and continuous underground gasification without prior mining preparation of the coal seam.

By the early 1940s, it had become evident that the construction of underground gasification chambers through conventional mining methods was economically expensive. Furthermore, maintaining gasifier sealing and ensuring stable gasification conditions proved technically challenging. Consequently, UCG development expanded to several major coal basins, including the Donets, Kuznetsk, Moscow, Dnieper, and Angren basins, where a total of five industrial-scale production stations and two experimental stations were established.

Air was the most commonly used gasification agent, while oxygen-enriched air was applied at the Lisichansk station in the Donets Basin. Approximately 25% of the generated heat was lost through the evaporation of formation water. Increasing the oxygen concentration helped maintain the high temperatures required for efficient gasification. Experiments were conducted under a wide range of geological conditions involving different coal types, seam thicknesses ranging from 0.8 to 22 m, depths between 30 and 350 m, ash contents from 2.3% to 34.3%, and calorific values between 7.95 and 30.64 MJ/kg.

Overall, approximately 14 million tons of coal were gasified, producing more than 40 billion Nm^3 of product gas. The syngas was utilized for electricity generation, district heating systems, and as a feedstock for the chemical industry. Depending on coal quality, gas yields varied between 1.5 and 5.5 Nm^3 per kilogram of coal gasified.

At the Moscow Basin station, filtration gasification and hydraulic fracturing techniques were successfully applied. The produced gas supplied the boiler plants of the city of Tula. After removal of sulphur compounds from the syngas, approximately 22,000 tons of elemental sulphur and 47,000 tons of sodium thiosulphate were recovered as valuable by-products. The station remained in continuous operation for 24 years before being closed in 1964 following depletion of the coal reserves.

The Yuzhno-Abinsk station was developed in steeply dipping bituminous coal seams (50–60°) with medium (1.8–3.0 m) and thick (8.0–9.0 m) seam thicknesses at a depth of approximately 350 m. The produced gas supplied industrial facilities located within a radius of 15–20 km around the city of Kiselyovsk. Maximum gas production reached approximately 70,000 Nm^3/h, while the highest annual production exceeded 450 million Nm^3, corresponding to the gasification of approximately 190,000 tons of coal.

Compressed air was injected at various operating pressures, including low pressure (approximately 25 bar), medium pressure (up to 80 bar), and high pressure (up to 500 bar). The produced gas reached temperatures of approximately 700°C upon arrival at the surface. Primary cooling was achieved within the production wells through water injection, after which the gas passed through cascade scrubbers where it was further cooled, cleaned of tar and dust, and stripped of excess steam depending on combustion-front conditions. The hydrogen concentration in the produced gas was approximately twice the normal level owing to the thermal decomposition of steam. During the operational lifetime of the station, three different underground gasifier

configurations were developed and tested, each demonstrating varying degrees of technical success.

Table. 2 Production results of underground gasification in the USSR stations

Parameter	Unit	Yuzhno-Abinsk	Podmoskovnaya	Angren
Years of operation	years	37	24	31
Operating period	year	1955–…	1940–1964	1961–…
Coal calorific value	MJ/kg	29.09	11.39	15.07
Coal type	–	Bituminous coal	Lignite	Lignite
Syngas calorific value	MJ/Nm³	4.19	3.35	3.52
Specific gas yield	Nm³/kg coal	4.9	2.3	3.0
Gasification efficiency	%	70	69	70
Gas composition				
Water vapour (H_2O)	%	0.02	1.2	0.4
Carbon dioxide (CO_2)	%	13.7	17.6	19.5
Higher hydrocarbons (C_2H_m)	%	0.2	0.2	0.3
Oxygen (O_2)	%	0.2	0.5	0.6
Hydrogen (H_2)	%	14.9	15.2	17.0
Carbon monoxide (CO)	%	11.8	6.0	5.4
Methane (CH_4)	%	2.7	1.5	2.0
Nitrogen (N_2)	%	56.48	57.8	54.8
Coal gasified	$\times 10^3$ t	2	5	6
Syngas produced	$\times 10^6$ Nm³	7	5	16
Coal recovery	%	50.3	29.4	62.2

The average annual operating parameters of the station were as follows:

- **Syngas production:** 280 million Nm³/year
- **Average calorific value of syngas:** 3.79 MJ/Nm³
- **Coal gasified:** 66,100 t/year
- **Coal recovery (gasification efficiency):** 43.4%
- **Actual-to-designed production capacity:** 56.0%

The Angren UCG station was developed for the gasification of thick lignite seams ranging from 6 to 20 m in thickness. The project demonstrated that syngas produced from underground coal gasification could be economically utilized for electricity generation in thermal power plants. The total proven coal reserves amounted to approximately 20 million tons, of which about 12 million tons were considered suitable for underground gasification. The coal seams were characterized by low groundwater saturation and low permeability.

Directional drilling technology was applied, with borehole lengths reaching up to 65 m. Well-linking operations required injection pressures ranging from 300 to 600 bar, whereas gasification itself was conducted at relatively low operating pressures of 20–60 bar. The maximum

annual gas production reached approximately 1.41 billion Nm³, corresponding to the gasification of about 600,000 t of lignite.

In 1981, energy costs accounted for approximately 34.5% of the total syngas production costs, while compressed air represented approximately 67% of the total energy consumption associated with the process.

The average annual operating parameters of the Angren station were as follows:

- **Syngas production:** 299 million Nm³/year
- **Average calorific value of syngas:** 2.89 MJ/Nm³
- **Coal gasified:** 102,000 t/year
- **Coal losses:** 25,400 t/year
- **Specific gas yield:** 2.96 Nm³/kg of coal gasified
- **Gas production per unit volume of injected air:** 1.18 Nm³/Nm³ of air
- **Gas losses relative to the theoretical yield:** 7.8%
- **Syngas not meeting quality specifications:** 23.4 million Nm³/year

Development of Underground Coal Gasification (UCG) Technology in North America

North America, particularly the United States and Canada, has played a role key in the scientific and technological development of Underground Coal Gasification (UCG). Unlike European research, which primarily focused on the application of UCG in deep coal deposits, the U.S. program was organized as a national research initiative aimed at developing different technological concepts, optimizing process parameters, and establishing the foundation for future commercial implementation.

Beginning of organized research

In the early 1970s, the U.S. Department of Energy established three specialized research programs, each dedicated to investigating a different category of coal deposits:

- Eastern coal deposits—thin seams (up to approximately 3 m), gently dipping, containing high-quality bituminous coal;
- Western coal deposits—thick sub-bituminous coal seams;
- Lignite deposits—with relatively low calorific value.
- This approach enabled the development of UCG technologies specifically adapted to different geological conditions and coal types.

MERC – Princetown research program

The Morgantown Energy Research Center (MERC) was responsible for research on eastern coal deposits. Two pilot projects were conducted at the Pricetown experimental site, with the most significant results achieved during the Pricetown II experiment.

Within this project, the Longwall Generator Concept was developed, inspired by the longwall underground mining method. The basic concept was based on allowing the gasification front to advance naturally along the coal seam, thereby increasing coal recovery. The connection between injection and production wells was established using directional drilling, significantly reducing the number of wells required while improving process control and roof stability. Despite the encouraging technical results, the program was terminated in 1983 following reductions in federal funding for fossil energy research

Lawrence Livermore Laboratory Program

In parallel with MERC, Lawrence Livermore Laboratory (LLL) initiated its own UCG research program in 1972. The primary objective was to develop an *in situ* gasification technology capable of producing medium-calorific-value syngas suitable for subsequent industrial processing.

The initial concept involved the use of controlled explosive charges to create highly permeable zones within deep coal seams. Later, additional techniques, including reverse combustion linking and directional drilling, were incorporated into the research program.

Three pilot tests were conducted at the Hoe Creek experimental site. During the third experiment, a system consisting of five vertical wells connected by a horizontal directional borehole within the coal seam was implemented. Although reverse combustion did not produce the expected results, oxygen-enriched air successfully established communication between the wells at an average propagation rate of approximately 44 m/day. Over a period of 47 days, approximately 3,900 t of coal were gasified, producing syngas with an average calorific value of 7.4 MJ/m³ and a composition of approximately 37% H_2, 11% CO, 5% CH_4, and 44% CO_2.

Hanna Experiments

The most comprehensive U.S. UCG research program was conducted by the Laramie Energy Research Center at the Hanna experimental site in Wyoming. Beginning in the mid-1970s, four successive field experiments significantly improved the understanding of underground coal gasification processes.

During the Hanna II experiment, researchers found that increasing the air injection rate had little influence on the composition or calorific value of the produced syngas. Instead, the position of the channel connecting the injection and production wells proved to be much more important, as it facilitated the continuous involvement of fresh coal within the reaction zone.

The third phase of the program investigated the influence of operating pressure. Lower operating pressures resulted in increased groundwater inflow, which reduced the calorific value of the produced syngas.

Hanna III, conducted in 1977, represented the first U.S. experiment specifically designed to investigate the environmental impact of UCG on groundwater systems. It also demonstrated that insufficient water availability within the reaction zone caused excessive temperature increases and a gradual deterioration of syngas quality.

The Hanna IV experiment evaluated larger spacing between injection and production wells together with the influence of injected air volume on the width of the reaction zone. Energy balance analyses indicated that approximately 66% of the coal energy was converted into syngas, about 18% remained underground, while the remaining energy was lost through heat transfer to the surrounding rock mass.

Rawlins – Gasification of Steeply Dipping Coal Seams

A separate direction of U.S. UCG research was represented by the Rawlins experiments conducted by Gulf Research and Development Company and TRW Systems Inc. in Wyoming. Their objective was to develop UCG technology for steeply dipping coal seams (>35°), which were considered uneconomic using conventional underground mining methods.

During the Rawlins I experiment (1979), approximately 980 t of coal were gasified over a 30-day period, producing syngas with an average calorific value of 5.6 MJ/m³. Approximately 80% of the coal energy was converted into gaseous products. The experiments also demonstrated that increasing operating pressure reduced the concentration of solid particles in the produced gas.

Even better results were obtained during Rawlins II (1981). Coal gasification rates exceeded 180 t/day, while syngas composition could be effectively controlled by adjusting the oxygen-to-steam ratio together with operating pressure. The produced syngas contained approximately 23% methane, and higher operating pressures further increased its calorific value.

The experiments demonstrated that the highest coal recovery (approximately 88%) was achieved using inclined injection wells drilled along the dip direction of the coal seam. They also confirmed that oxygen–steam mixtures are substantially more effective gasification agents than air because they produce medium-calorific-value syngas with higher hydrogen and methane contents and virtually no nitrogen dilution, resulting in significantly improved gas quality.

Modern Development of UCG in North America

Throughout the 1980s and early 1990s, the United States was the global leader in UCG research and development. However, the sharp decline in natural gas prices during the mid-1990s resulted in the termination of most research programs.

Interest in UCG re-emerged around 2005 when Lawrence Livermore National Laboratory (LLNL), with financial support from the U.S. Department of Energy (DOE), initiated a new generation of research focused on developing integrated three-dimensional numerical models for simulating underground gasifier growth. Modern modelling approaches integrate chemical reactions, geomechanics, heat transfer, groundwater flow, and fluid dynamics, allowing significantly more accurate simulation of the complete gasification process (Burton, 2007).

At the same time, private companies including Linc Energy, Carbon Energy, Laurus Energy, and Ergo Exergy initiated preparations for several commercial-scale pilot projects in Wyoming, North Dakota, Alaska, and Alberta. (Zamzow, 2010). Many of these projects were designed to integrate UCG with carbon capture and storage (CCS) technologies as well as Gas-to-Liquids (GTL) fuel production.

In Canada, the most significant project was the Swan Hills Synfuels pilot, conducted within the Manville coal formation at a depth of approximately 1,400 m, representing the deepest UCG field experiment performed worldwide. The project demonstrated that syngas with a calorific value of approximately 10 MJ/m³ could be successfully produced even at such depths, confirming the technical feasibility of deep underground coal gasification.

Current UCG research in North America is increasingly focused on integrating underground coal gasification with hydrogen production, synthetic liquid fuel production, and CCS technologies. Consequently, the knowledge and experience gained through U.S. and Canadian experimental programs constitute one of the most important scientific foundations for the future commercialization of underground coal gasification (Yang, 2016).

Development of Underground coal gasification technology in Europe

The development of Underground Coal Gasification (UCG) technology in Europe has been closely linked to global energy demand, the availability of fossil fuels, and advances in mining technology. Following the successful experiments conducted in the former Soviet Union, interest in this technology expanded to Western Europe, where intensive research began after the Second World War with the aim of utilizing deep and economically unmineable coal reserves.

The first European experimental investigations were carried out between 1944 and 1959 in Belgium, France, the United Kingdom, Italy, Poland, and Czechoslovakia. During this initial phase, experiments were mainly conducted in thin and relatively shallow coal seams, with access to the coal deposits provided through underground mine workings or a combination of underground workings and vertical boreholes. Air at low pressure (1.2–1.5 bar) was commonly used as the gasification agent, resulting in the production of low-calorific syngas with a heating value generally not exceeding 2.6 MJ/Nm³. The produced gas contained high concentrations of carbon dioxide and relatively low concentrations of carbon monoxide due to the limited interaction between the gasification agent and the coal seam. Coal recovery during this period rarely exceeded 50%.

The development of the technology was interrupted in the early 1960s due to the sharp decline in crude oil prices, which significantly reduced interest in alternative energy production technologies. A new wave of research began in 1974, immediately following the first global oil crisis, when the need to utilize domestic energy resources once again became a strategic priority.

During this new phase of development, European research focused on the gasification of deep hard coal seams, typically at depths exceeding 800 m. Unlike the earlier experiments, advanced technologies such as hydraulic fracturing, reverse combustion linking, and directional drilling were introduced. As a result, Western Europe became a leading region in the development of UCG for deep coal deposits, significantly surpassing the depths achieved in contemporary Soviet and U.S. experiments, which generally did not exceed 350 m.

The most significant European project of this period was the Belgian–German experiment at Thulin, initiated in 1978. The primary objective of the project was to demonstrate the feasibility of commercial UCG application under typical European geological conditions and to produce syngas suitable for electricity generation, fuel gas production, and chemical products such as methanol. The project also investigated the operational lifetime of the underground gasifier, the optimum gasification chamber width, and the efficiency of different gasification methods. In addition to field experiments, the project included laboratory investigations and mathematical modelling to improve the understanding of the physical and chemical processes occurring within the underground gasifier.

Between 1982 and 1984, several attempts were made to connect vertical process wells using the reverse combustion linking method in a coal seam approximately 1.5 m thick at a depth of 860 m. These experiments demonstrated that coal behaviour at great depths differs substantially from that observed in shallow deposits. High lithostatic pressure compressed the coal and significantly reduced its natural permeability, preventing the formation of the branched combustion front required for successful well linkage. Although a thermally altered (distilled) coal zone with improved permeability developed around the injection wells, this proved insufficient for successful application of the reverse combustion method.

Following the failure of reverse combustion linking, short-radius directional horizontal drilling was introduced in 1986, representing a major technological breakthrough. Combined with the injection of oxygen and water at high pressures (190–270 bar), this approach produced syngas with a calorific value ranging from 7.1 to 11.0 MJ/Nm³ and a methane content of 17–25.5%. Gas production rates reached 92–177 Nm³/h. During the experiments, approximately 8,638 t of coal were included within the gasification area, of which about 3,835 t were successfully gasified, corresponding to a coal recovery of 44.4%. The overall energy conversion efficiency from coal to syngas reached approximately 44.8%, with around 20% of the original coal energy converted into useful fuel gas, while the remainder was lost as ungasified coal or heat transferred to the surrounding rock.

The Thulin experiments demonstrated several important technical advantages. High injection pressures enabled the production of syngas with a relatively high methane concentration without significantly reducing its calorific value. Furthermore, oxygen and foamed water proved to be suitable gasification agents that could be compressed and transported using relatively simple equipment. It was also established that lateral expansion of the gasifier created a natural filtration zone composed of residual coal, preventing direct oxygen breakthrough into the production well and thereby avoiding combustion of the produced syngas.

Alongside the technical investigations, comprehensive economic assessments were conducted. These studies showed that the largest share of UCG investment costs was associated with drilling, well completion, and maintenance of the technological wells, whereas surface installations represented a considerably smaller proportion of the total capital investment. The analyses also indicated that drilling costs could be progressively reduced through operational experience, improved geological knowledge, and optimization of drilling procedures.

The European working group concluded that the most economically attractive application of UCG-derived syngas was electricity generation. For a power plant with an installed capacity of approximately 300 MW, the required investment was estimated at around 196 million ECU. Economic evaluations indicated that UCG could become competitive with conventional coal-fired power plants when applied to coal deposits at depths of approximately 1,000 m, with gasifier widths exceeding 30 m and a geometric recovery factor of about 0.75.

During the 1990s, UCG activities in Europe declined once again, mainly due to stabilized energy prices and the limited technological maturity of the process. Nevertheless, research activities did not cease completely. In Russia, efforts continued to improve gasifier designs and operating parameters, resulting in several patented technological innovations. In Ukraine, research continuity was maintained through the development of hydrogen production technologies based on syngas and active participation in European collaborative research programs.

Since the beginning of the twenty-first century, interest in UCG has increased again, largely driven by the need to reduce greenhouse gas emissions and improve the utilization of deep coal resources. Between 2007 and 2014, the European Union funded several major projects, including HUGE and HUGE2, involving Poland, Ukraine, and numerous European research institutions. These projects focused on hydrogen-rich syngas production, process modelling, groundwater impact assessment, operational safety, and the integration of UCG with carbon capture and storage (CCS) technologies. During the same period, Bulgaria conducted a comprehensive feasibility study for the application of UCG in the Dobrudzha coal deposit, while Hungary initiated activities aimed at constructing a pilot UCG facility in the Mecsek region [5].

The United Kingdom also renewed interest in offshore coal resources by issuing several exploration licences for potential UCG projects in coastal offshore areas [6].

Development of Underground coal gasification technology in Australia

Australia is one of the countries that achieved the greatest progress in the practical application of Underground Coal Gasification (UCG) technology during the early twenty-first century. From the late 1990s until 2012, the country became the world's leading demonstration site for UCG, with several pilot projects confirming both the technical feasibility of the technology and its potential for commercial deployment.

The development of UCG in Australia began with the Chinchilla project, located approximately 350 km west of Brisbane in the state of Queensland. Site selection commenced in November 1997, while construction activities were completed by the end of 1999, when syngas production also began. The pilot project officially operated from 1999 to 2003, although preparatory activities had started in 1997, and it is widely regarded as the largest Western demonstration project for underground coal gasification.

The UCG technology was developed through a collaboration between the Canadian company Ergo Exergy Technologies Inc. and the Australian company Linc Energy Ltd. Ergo Exergy provided the technological concept and engineering design of the underground gasifier, whereas Linc Energy was responsible for constructing and operating the demonstration facility. The project represented the first integrated application of UCG combined with technologies for electricity generation and synthetic liquid fuel production.

The long-term strategy envisioned two principal applications for the produced syngas: electricity generation using an Integrated Gasification Combined Cycle (IGCC) power plant and the production of liquid fuels through Fischer–Tropsch synthesis, commonly referred to as Gas-to-Liquids (GTL) technology.

To support these objectives, a syngas treatment and cleaning facility was constructed. After leaving the underground gasifier, the syngas was first cooled, allowing condensable liquid products to be separated for storage or further commercial processing. The gas was subsequently purified using sintered metal filters to remove particulate matter and other impurities, making it suitable for use in a gas turbine. In addition, a pilot-scale gas-cleaning unit was built to simulate the operating conditions of a future commercial plant.

Because of the specific geological characteristics of the Chinchilla coal deposit, particularly its relatively shallow depth and the higher permeability of the overlying strata, the produced syngas had to be compressed before entering the gas turbine. A gas compressor was therefore installed to increase the gas pressure to the required operating level. The separated process water was recycled for syngas cooling, compressor cooling, and as part of the water cycle intended for the future steam turbine. Studies indicated that in deeper coal seams or formations with lower permeability, the gasification process could operate at considerably higher pressures, thereby eliminating the need for additional gas compression.

The project also included plans for constructing a demonstration IGCC power plant with an installed capacity of 70 MW, intended to minimize initial capital investment while generating sufficient technical and economic data for future commercial development. The long-term

objective was to expand the facility gradually to approximately 400 MW, which was considered the optimum capacity for commercial operation.

During the experimental program, nine technological wells were drilled to gasify a coal seam approximately 10 m thick at a depth of about 140 m. Syngas production reached approximately 80,000 Nm^3/h, corresponding to an electricity generation potential of about 70 MW. Approximately 35,000 t of coal were gasified during the trials, producing more than 80 million Nm^3 of syngas with an outlet temperature of around 300°C. These results represented one of the most successful demonstrations of UCG worldwide and confirmed the possibility of stable and long-term process control.

Parallel to the activities of Linc Energy, Carbon Energy Ltd. developed its own underground coal gasification technology and constructed two experimental gasifiers. The produced syngas was successfully used to operate a 1 MW demonstration power plant, providing further evidence of the practical applicability of UCG for electricity generation [7].

During the same period, other companies, including Cougar Energy, also initiated the development of their own UCG projects. However, following environmental problems associated with the Kingaroy pilot project, comprehensive scientific investigations were undertaken to assess potential impacts on groundwater resources and the surrounding environment. As a consequence, the Government of Queensland introduced significantly stricter regulatory requirements for future UCG developments.

An independent scientific assessment of environmental risks was subsequently completed, after which every project developer was required to demonstrate the feasibility of safe underground gasifier closure and site rehabilitation (decommissioning) before obtaining approval for new UCG operations. Through these measures, Australia established one of the world's most stringent regulatory frameworks governing underground coal gasification.

Despite the introduction of stricter environmental regulations, Australia continued investing actively in carbon capture and storage (CCS) technologies. A particularly important initiative is the CarbonNet project in the state of Victoria, which aims to develop large-scale CO_2 storage infrastructure and facilitate the integration of UCG with greenhouse gas emission reduction technologies. Australia has also established active scientific collaboration with several European research institutions in the field of integrated UCG–CCS systems.

The experience gained from the Chinchilla project, together with other Australian demonstration projects, provides an important foundation for the modern development of underground coal gasification. These projects demonstrated that UCG can successfully operate under near-commercial conditions while simultaneously confirming that its long-term implementation requires rigorous environmental monitoring, an appropriate regulatory framework, and integration with carbon capture and storage technologies to minimize greenhouse gas emissions

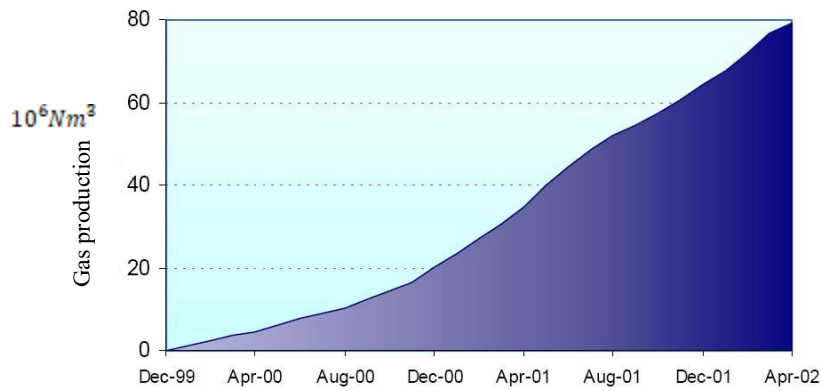


Fig. 2 History of production of gas in Chincila [8]

Development of Underground coal gasification technology in Asia

Asia is one of the regions with the greatest potential for the development and application of Underground Coal Gasification (UCG) technology, primarily due to its vast coal reserves and the increasing demand for cleaner energy technologies. The most significant progress in UCG development has been achieved in **China, India, and Pakistan**, where research has focused on the utilization of deep, inaccessible, and economically unmineable coal resources.

Development of UCG technology in China

China possesses one of the world's largest coal resource bases. Its proven coal reserves are estimated at approximately **114.5 billion tones**. However, due to the limitations of conventional mining methods, nearly **50%** of the country's coal resources are considered uneconomical for traditional extraction. This has been one of the principal drivers behind China's growing interest in Underground Coal Gasification as an alternative method for exploiting deep coal deposits.

Interest in UCG has also been stimulated by China's national strategy to reduce pollution associated with coal-fired power generation. UCG enables the production of synthesis gas (syngas) underground, potentially reducing the need for surface mining operations while providing improved control of environmental emissions.

To date, approximately **15 experimental UCG projects** have been implemented in China. A major contribution has been made by the **Underground Coal Gasification Research Centre** at the **China University of Mining and Technology – Beijing (CUMTB)**. The research center conducts theoretical studies, laboratory investigations, numerical modelling, and field-scale experiments aimed at optimizing the gasification process, improving process control, and evaluating environmental impacts.

In cooperation with the Chinese coal industry, CUMTB has played an active role in advancing the development and commercialization of UCG technology. Owing to the strategic importance of UCG, China has also sought to strengthen international collaboration with countries and organizations experienced in underground coal gasification.

One of the leading Chinese companies involved in UCG development is **ENN Group**, a subsidiary of **XinAo Group**, one of China's largest private energy companies. The company collaborates with CUMTB as well as with research institutions and industrial partners from Uzbekistan, the United States, Australia, South Africa, and the European Union to accelerate the development and commercial deployment of UCG technology.

In 2011, an important international partnership was established between the British company **Seamwell International Ltd.** and the **Chinese Energy Conservation and Environmental Protection Group (CECEP)**. The project proposed the underground gasification of approximately **6 million tonnes of coal annually** in the **Yi He coalfield** in Inner Mongolia, with the objective of generating approximately **1,000 MW** of electricity over a projected operating period of **25 years**. In addition, the Australian company **Carbon Energy Ltd.** developed a commercial UCG project in the **Haoqin coalfield** located in the **Xiwuqi region of Inner Mongolia**. The project was implemented through a **Technology License Agreement (TLA)** with **Zhengzhou Coal Industry Group Co. Ltd.**, under which Carbon Energy was selected as the exclusive technology partner for underground coal gasification in China [9].

Development of UCG technology in India

India, one of the world's largest producers and consumers of coal, has also shown considerable interest in the development of Underground Coal Gasification technology. Particular attention has been directed toward the utilization of lignite and coal deposits that cannot be economically extracted using conventional mining techniques.

In 2005, **Neyveli Lignite Corporation** launched a national UCG program supported by the **Ministry of Coal of India** to identify suitable locations for pilot UCG projects. The program included the selection of appropriate coal blocks, pilot-scale testing, and evaluation of the calorific value of the produced synthesis gas.

Subsequently, the **Central Mine Planning & Design Institute Limited (CMPDI)** prepared comprehensive geological and technical assessments for five potential UCG sites. To provide an independent technical evaluation, the **Skochinsky Institute of Mining (SIM)** of Russia was commissioned to review the project.
Among the investigated locations, the **Kasta Block** within the **Raniganj Coalfield** was identified as the most promising site, where exploration drilling was completed in preparation for a pilot UCG project. In addition, **Coal India Limited (CIL)** identified two further coal blocks suitable for future commercial UCG development: **Kaitha Block** and **Thesgora "C" Block** (Khads, 2007).

Development of UCG technology in Pakistan

In Pakistan, UCG development is closely associated with the enormous reserves of low-grade lignite located in the **Thar Coalfield**, one of the country's largest untapped energy resources.

In December 2009, the **Thar Coal and Energy Board (TCEB)** established a public–private partnership with international companies and research institutions from China, Germany, and South Africa to investigate the geological, hydrogeological, environmental, and social aspects of utilizing the Thar coal resources.

The primary objective of the program was to develop a production system capable of utilizing approximately **6.5 million tonnes of coal annually** and supporting the construction of power generation facilities with a capacity of approximately **1,200 MW**. In 2010, a UCG pilot project was initiated in **Block V of the Thar Coalfield**, where the reserves of low-grade lignite are estimated at approximately **1.4 billion tonnes** (Khurshid, 2011).

The project included the construction of two pilot power plants, each with a generating capacity of **5 MW**, with the long-term objective of producing approximately **8,000 MW** of electricity from the Thar coal resources. However, several technical challenges emerged during the construction and commissioning phases, particularly concerning:

- establishing a stable linkage between injection and production wells;
- groundwater inflow into the gasification zone;
- characterization of surrounding aquifers;
- controlled ignition and stabilization of the underground gasification process.

Despite these technical challenges, the project represents an important milestone in the development of UCG technology in South Asia and demonstrates the potential for utilizing extensive but otherwise inaccessible coal resources through advanced underground gasification technologies.

Table 3 Globally significant underground coal gasification tests (Perkins, Underground coal gasification-Part I: field demonstrations and process performance, 2018) (L. Jiang, 2022)

Country	Site	Startup year	Coal type	Technique	Injected gas	Seam depth(m)	Seam thickness(m)
Former	Lisichansk	1935	Bit.	SDB	Air	30	1
U.S.S.R.	Podmoskovna	1947	L	LVW	Air	55	3
	Yuzno-Abinskaja	1955	Bit.	SDB	Air	~100	3
	Shatskaya	1959	L	LVW	Air	50	2
	Angrenskaja	1961	L	LVW	Air	150	9
USA	Hanna I	1973	HVC	LVW	Air	120	9
	Hanna II	1975	HVC	LVW	Air	85	9
	Hanna III	1977	HVC	LVW	Air	85	9
	Hoe Creek I	1976	HVC	LVW	Air	40	8
	Hoe Creek IIA	1977	HVC	LVW	Air	40	8
	Hoe Creek IIB	1977	HVC	LVW	O_2/H_2O	40	8
	Hoe Creek IIIA	1979	HVC	LVW	Air	40	8
	Hoe Creek IIIB	1979	HVC	LVW	O_2/H_2O	40	8
	Pricetown I	1979	Bit.	LVW	Air	270	2
	Rawlins IA	1979	SB	SDB	Air	105	18
	Rawlins IB	1979	SB	SDB	O_2/H_2O	105	18
	Centralia A	1984	SBC	K-CRIP	O_2/H_2O	75	6
	Centralia B	1984	SBC	LVW	O_2/H_2O	75	6
	Rocky Mountain IA	1987	SB	K-CRIP	O_2/H_2O	110	7
	Rocky Mountain IB	1987	SB	LVW	O_2/H_2O	110	7
UK	Newman-Spinney P5	1949	SB	BH	Air	75	1
Belgium	Thulin	1986	A	LVW	Air	860	6
Spain	El Tremedal	1997	SB	L-CRIP	O_2/H_2O	580	2
Poland	Wieczorek	2014	SB	SM	Air, O_2, CO_2	464	5.5
China	Xinhe	1994	Bit.	LT	Air/Steam	80	3.5
	Liuzhuang	1996	HVC	LT	Air/Steam	100	3
	Xinwen	2000	HVC	LT	Air/Steam	100	1.8
	Feichang	2001	Bit.	LT	Air	90	1.5
	Xiyang	2001	A	LT	Air/Steam	190	6
Australia	Chinchilla G1	2000	SB	LVW	Air	132	10
	Chinchilla G3	2007	SB	LVW	Air	132	10
	Chinchilla G4	2009	SB	P-CRIP	Air	132	10
	Chinchilla G5	2011	SB	L-CRIP	Air&O_2/H_2O	132	5.5
	Bloodwood Ck, Panel 1	2009	SB	P-CRIP	Air&O_2/H_2O	200	9
	Bloodwood Ck, Panel 2	2011	SB	P-CRIP	Air	200	9
Canada	Swan Hills	2011	HVB	L-CRIP	O_2/H_2O	1400	4.5

Guide to symbols Coal type: L = lignite, SB = subbituminous, SBC = subbituminous C, Bit. = bituminous, HVB = high volatile bituminous B, A = Anthracite. Technique: LVW = linked vertical wells, CRIP = controlled retracting injecting point, L-CRIP = linear CRIP, P-CRIP = parallel CRIP, K-CRIP=Knife-edge CRIP, SDB = steeply dipping beds, BH = borehole method, LT = long tunnel, SM = shaft method.

Underground coal gasification in South Africa

South Africa is one of the African countries with considerable interest in the development and application of Underground Coal Gasification (UCG) technology, primarily due to its extensive coal reserves and the need to secure additional energy resources while reducing environmental impacts.

The first investigations into the application of UCG in South Africa were initiated by **Eskom**, one of the country's largest electricity producers. In 2007, Eskom commissioned a pilot UCG project adjacent to the **Majuba Power Station** in the Mpumalanga Province. The pilot plant was designed with a capacity of approximately **3 MW** to evaluate the technical feasibility of the gasification process and to assess the potential utilization of the produced synthesis gas (syngas) within the power generation sector.

In 2010, the syngas produced through the UCG process was successfully utilized for **co-firing with coal** at the Majuba Power Station, demonstrating the feasibility of integrating underground coal gasification with existing coal-fired power plants [10].

The **Majuba coal deposit** consists of bituminous coal seams ranging from **1.8 to 4.5 m** in thickness and located at depths of approximately **250–380 m**. These geological characteristics make the deposit well suited for UCG technology, particularly because they enable the exploitation of coal resources that are difficult or uneconomical to recover using conventional mining methods.

In addition to Eskom's activities, **Sasol Limited**, internationally recognized for its Coal-to-Liquids (CTL) technology, has investigated the potential application of UCG as a source of syngas for its Gas-to-Liquids (GTL) processes at the **Secunda** complex. Sasol and Eskom established a

collaborative initiative with an estimated value of approximately **ZAR 1 billion**, aiming to support the development and future commercialization of UCG technology in South Africa.

Besides the Eskom and Sasol initiatives, several other UCG projects have been considered across Africa. Among these are the Sub-Saharan Africa project developed through collaboration between **Linc Energy** and **Exxaro Resources**, as well as the **Theunissen Project**, initiated by **Africary Holdings Ltd.** These initiatives reflect the growing interest in evaluating UCG as a viable technology for the utilization of deep and otherwise inaccessible coal resources.

The experience gained in South Africa demonstrates that UCG technology has significant potential for exploiting deep and economically unmineable coal reserves, particularly in countries where coal remains a major component of the energy mix. However, the successful commercial deployment of the technology will depend on further improvements in process control, groundwater protection, environmental monitoring, and the implementation of robust regulatory frameworks that ensure safe and sustainable operation.



Figure 3. Worldwide underground coal gasification: a snapshot (Yang, Recent Development on Underground Coal Gasification and Subsequent CO2 Storage, 2016)

CHALLEMGES FOR THE COMMERCIALIZATION OF UNDERGROUND COAL GASIFICATION

Despite decades of development and significant technological progress, Underground Coal Gasification (UCG) has not yet achieved widespread commercial deployment. Recent studies indicate that the successful implementation of UCG depends not only on the technical feasibility of the process but also on its economic viability, environmental risk management, regulatory frameworks, and social acceptance [11].

In recent years, substantial improvements have been achieved in controlling the gasification process through the application of advanced numerical modelling, Computational Fluid Dynamics (CFD) simulations, Digital Twin technology, artificial intelligence, and real-time monitoring systems. These technologies enable better control of the combustion zone, a more stable syngas composition, higher energy efficiency, and improved utilization of coal resources. Furthermore, advances in directional drilling and modern well-linking technologies have significantly enhanced the reliability and controllability of the UCG process.

The greatest challenges to commercialization remain closely related to environmental protection. Particular attention is focused on the potential contamination of groundwater by organic compounds, phenols, benzene, polycyclic aromatic hydrocarbons (PAHs), and other gasification by-products, as well as on controlling land subsidence and preventing syngas migration into surrounding geological formations. Consequently, modern UCG projects incorporate continuous hydrogeological monitoring, geophysical surveys, three-dimensional

geomechanical modelling, and groundwater quality monitoring throughout the entire project life cycle [11].

Practical experience demonstrates that UCG is a highly site-specific technology. Therefore, selecting a suitable coal deposit is one of the most critical prerequisites for successful commercial operation. The assessment of coal seam suitability requires comprehensive evaluation of seam thickness and depth, physical and mechanical properties, structural and tectonic characteristics, hydrogeological conditions, surrounding rock permeability, and the potential risk of surface subsidence. Today, such assessments are increasingly performed using integrated geological–geomechanical models and multi-criteria decision-making methods.

An additional challenge is gaining public confidence and ensuring the social acceptance of the technology. The failures of several UCG projects in the past have highlighted the importance of transparent monitoring, well-defined regulatory frameworks, and continuous communication with local communities. Modern UCG development concepts are based on the principles of sustainable resource management, comprehensive risk assessment, and compliance with environmental regulations aimed at minimizing environmental impacts.

Economic viability represents another key factor influencing the future development of UCG. Syngas produced through underground coal gasification is no longer considered solely as a fuel for electricity generation but also as a valuable feedstock for the production of hydrogen, ammonia, methanol, synthetic liquid fuels, and other high-value chemical products. Particular emphasis is currently placed on integrating UCG with blue hydrogen production, carbon capture and storage (CCS), and low-carbon fuel technologies, which could substantially improve both the economic performance and environmental sustainability of the process.

In the future, the greatest potential for the commercial application of UCG is expected in countries possessing large reserves of deep, unmineable coal deposits and facing increasing demand for domestic energy resources, such as China, India, Australia, and South Africa. Nevertheless, broader commercialization will depend on the successful integration of advanced monitoring technologies, digitalization, risk management strategies, and greenhouse gas emission reduction technologies, together with the establishment of stable regulatory frameworks capable of enhancing investor confidence.

CONCLUSION

The analysis of the historical development of Underground Coal Gasification (UCG) demonstrates that, although the concept has been known for more than a century, significant technological progress has been achieved only during the last few decades, driven by advances in directional drilling, modern process control techniques, numerical modelling, and integration with advanced energy technologies.

The experience gained from the former Soviet Union, the United States, Europe, Australia, China, India, Pakistan, and South Africa confirms that UCG is a technically feasible technology capable of providing stable syngas production for applications such as electricity generation, hydrogen production, synthetic liquid fuels, and a wide range of chemical products. In particular, recent demonstration projects indicate that the technology is steadily progressing toward higher levels of technological maturity.

At the same time, the analysis shows that the commercialization of UCG continues to face significant challenges. The most critical issues include ensuring reliable control of the gasification process, protecting groundwater resources, controlling greenhouse gas emissions, managing the risk of surface subsidence, and establishing appropriate legal and regulatory frameworks. The economic viability of UCG projects depends largely on geological conditions, coal seam depth and thickness, coal quality, energy market prices, and the potential integration of UCG with hydrogen production and Carbon Capture and Storage (CCS) technologies.

Recent research indicates that integrating UCG with CCS, hydrogen production, and advanced digital modelling and real-time monitoring systems can significantly reduce CO_2 emissions while improving the overall energy efficiency of the process. In the context of the

global energy transition, UCG has the potential to serve as a transitional technology, enabling the more sustainable utilization of existing coal resources, particularly in countries with substantial reserves of deep and otherwise unmineable coal deposits.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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