

Review

Paul Younger's work on underground coal gasification with carbon capture and storage

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Abstract

The key features of Professor Paul Younger's work on Underground Coal Gasification (UCG) linked to Carbon Capture and Storage (CCS) are summarised, with particular reference to his work on protecting potable water aquifers from contamination by the by-products of *in-situ* gasification and on his development of a technical basis for secure storage of captured carbon dioxide (CO₂) in UCG cavities. A review of recent developments in the UCG field is presented, noting that the scale and international reach of demonstration projects has diminished over the intervening years and that the locus of research activity has moved to China and other Asian countries in which coal use continues at high levels. The importance in a climate-constrained world of a robust method of capturing and storing the CO₂ produced by UCG activity is highlighted. Developments in CCS linked to the UCG process itself are reviewed and a brief summary is provided of the present state of CCS technology more generally.

Keywords: Underground Coal Gasification (UCG); Carbon Capture and Storage (CCS); coal, gasification; carbon dioxide (CO₂)

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1. Introduction

To quote the opening words in Professor Paul Younger's paper on Underground Coal Gasification (UCG) with Carbon Capture & Storage (CCS): "Long after its gas and oil reserves have been exhausted, the UK will still have large onshore and offshore coal reserves, though most of these are beyond the reach of conventional mining techniques. Underground coal gasification can be directly coupled to carbon capture and storage to unlock these vast energy reserves without increasing greenhouse gas emissions" [1]. It is characteristic of Professor Younger that he chose to promulgate these ideas in the Royal Academy of Engineering's *Ingenia* publication which is sent out to all

post-primary schools in the UK as a means of raising the profile more widely and attempting to win hearts and minds. This fits with a man who was about to become Newcastle University's first Pro Vice Chancellor for Engagement. It is also characteristic of the man that when the UK Government withdrew the funding for a competition aimed at accelerating the development of carbon dioxide (CO₂) storage infrastructure [2]—and without such infrastructure the UCG proposition loses its environmental appeal—he turned his mind to other topics. With the recent re-awakening of Government and commercial interest in CO₂ storage infrastructure—usually under the banner of Carbon Capture Utilisation & Storage (CCUS) [3]—it is appropriate to take stock of developments in both UCG and CCS technology over the intervening years. For an introduction to the UCG-CCS concept, please see “Supplementary Materials”.

The *Ingenia* paper [1] highlights Professor Younger's status as a polymath who happily brought multiple disciplines together to collaborate. In this instance he extended his own knowledge of geology, hydrogeology, sub-sea coal mining and mine water remediation by bringing in expertise in directional drilling, CCS and chemical engineering. The paper summarises the stop-go history of UCG over the course of a century in various countries, explains the basic principles of gasification (or partial oxidation) to obtain a useful synthesis gas (or syngas), outlines recent developments in directional drilling which make it possible to create networks of injection and production wells across a large and complex geological space, describes the process for controlling the production rate and composition of syngas, provides a list of end uses for syngas in power generation and chemicals production, and outlines the basic principles behind storing CO₂ in supercritical form at depths in excess of 800 metres using a network of pipelines. A particularly novel idea presented in the paper was to store the captured CO₂ by reinjecting it into the zones of rubble known as “goaf” and the pore space that is created in overlying strata when coal is removed (in this case by gasification rather than conventional mining). The paper explains the concept of using zones of net compression to create leak-tight storage, and draws interesting comparisons between this mode of storage and more conventional approaches involving saline aquifers, depleted oil and gas wells and Enhanced Oil Recovery [4,5].

The above ideas are developed further in another paper that Professor Younger co-wrote with the present author [6]. The paper cites a figure of 18 trillion tonnes of global coal resource [7] compared with the more usually quoted figures of tens of billions of tonnes of mineable coal reserves as an indicator of the potential of UCG. It provides a condensed history of UCG developments around the world over a long period of history, and characterises the scale of activity at the time of writing

(2009) by referring to 15 operating UCG licences across eight countries. Being politically astute, Professor Younger points out that the distribution of coal resource around the world is very different to the distribution of oil and gas resource. Adding a humanitarian note, he points to the high death toll associated with coal mining operations in China and Ukraine, and contrasts this with what might be expected with remote, *in-situ* gasification of coal.

The paper [6] expands on the concept of storing captured CO₂ in UCG voids and the overlying strata as a means of offering a self-contained CO₂ capture and storage facility without recourse to extensive pipelines [6]. Professor Younger goes on to outline the evidence base derived from the predictable collapses that happen following longwall coal mining [8], and presents his own experimental data on goaf permeability [9], suggesting that CO₂ injection into UCG goaf ought to be about 2,000 times easier than injection into a saline aquifer [9]. He then extends this argument, in the context of total global coal resource, to demonstrate that the global capacity for storage of captured CO₂ in UCG voids and the superincumbent strata comes close to the figures often claimed for saline aquifers.

The scale of the opportunity is extended further by looking beyond syngas as a fuel to burn in gas turbines for power generation to cover also the production of a cleaner syngas suitable for synthesising the petrochemicals and transport fuels that are commonly derived from refined oil and gas [10]. This leads to synergies through interlinking different syngas production and CO₂ transportation networks. Several case studies linking power generation and industrial CO₂ management are included—which, to varying extents, are starting to come to fruition now after many years (see below under CCS progress).

The paper [6] points to four main challenges with moving from potential opportunity to reality [6]. The first is developing a professional approach to environmental risk management, taking account of aquifer classification and favouring deeper strata. The second is establishing an appropriate approach to UCG licensing given the number of different environmental permits required. The third is public acceptance—linked in part to the first two but also requiring meaningful public engagement. The fourth is the cost of demonstrating UCG at scale, at depth and over time, which tends to be dominated by drilling costs—with more work still required to demonstrate that the directional drilling technology developed initially for the oil & gas industry, and further developed for use in Coal Bed Methane and Enhanced Coal Bed Methane applications, can achieve the accuracy required for UCG.

Looking beyond the work described above, the remainder of this paper charts the progress that has been made in the intervening years in respect of both UCG and CCS.

2. Progress with UCG

The state of development of UCG technology at the time of writing of the above papers was largely as described in an IEA report on Underground Coal Gasification [7]. Another document used widely as a reference in the UCG industry at the time was the best practice guide from the Lawrence Livermore National Laboratory, issued in draft in 2006 and finally issued formally in 2019 [11]. As noted above, there were multiple operational and development projects happening around the world at that time. Since then, most of them have stopped, and most recent publications have related to laboratory work and modelling work. The sudden announcement in the UK in November 2015 that the £1bn competition aimed at promoting the development of CO₂ capture and storage facilities was being cancelled [2] presented UK demonstration projects with a major problem. UCG projects had been developed on the assumption that a facility for accepting CO₂ captured from UCG operations would become available on the timescale of the projects, and it has taken 9 years to get back to a similar position (see under CCS below).

Lavis & Mostade have published a somewhat pessimistic assessment of the prospects of commercialisation, citing two issues: environmental impacts from some pilot-scale UCG projects (notably in Australia); and slower than expected development of CCS [12]. Their view is that whilst there may still be an interest in the technology in countries whose coal resource is large relative to their oil and gas resources, the opportunity for UCG-CCS to serve as a bridging technology to a renewable energy future has been missed.

Sarhosis *et al.* have published a more optimistic assessment, reviewing the history of UCG laboratory-based research and field trials in Europe, summarising what has been learnt, and commenting on what would need to be done next to commercialise the technology in Europe, including technological advances to improve syngas quality and stabilise gas production rates [13].

Green has reported on recent field trials and modelling work, aimed principally at improving the control of the gasification process, understanding the environmental impact risks, and developing ways of interfacing with CCS technology [14]. The field trials were carried out nearly ten years ago, with modelling work continuing afterwards. Topics of interest include gas flows within the UCG cavity, spalling of material from the walls and roof, and tar formation. He recommends a focus on deeper coal seams and the use of new modelling techniques.

Perkins has published an extensive review of field demonstrations of UCG in the USA, Europe, Australia and Canada [15]. He charts the development of a variety of UCG methods and configurations, and looks at what has been learnt about how performance is affected by the rank,

depth and thickness of the target coal seams, by the choice of oxidant, and by the oxidant injection rate. He includes learning about the UCG process derived from observations made after completion of field trials based on analysing core samples and partial excavation of UCG cavities, encouraging those working on UCG modelling to make use of the data and the insights provided. His paper contains an informative tabulation of UCG operations over a period from 1935 to 2014 at depths of 30m to 1400m in coal seams ranging in thickness from 1m to 18m, noting the heating value observed in the resulting syngas stream. Based on data and insights from the above trials, he identifies five different zones (the permeable bed of ash and char, the void space above it, the cavity sidewall/roof, the near field immediately surrounding the growing cavity boundary, and the far field) and describes the phenomena occurring in each zone. He concludes that the CRIP method offers many advantages over other methods. Based on the above insights into UCG phenomena and on the successful and unsuccessful aspects of many trials, he provides guidelines on how to select suitable sites for UCG at commercial scale and how to select an oxidant that is appropriate to the chosen site and the intended end use of the syngas.

In a related paper [16], Perkins develops the above concept of identifying five different zones within a UCG operation, and explores the fundamental physics of what is happening in each zone, identifying the relevant chemical reactions and describing the thermo-mechanical behaviour. He reviews work by others on developing integrated models for forecasting syngas production rates, syngas composition, coal conversion rates and cavity shape, and makes recommendations for future work on the development of integrated models.

The most recent UCG field trial described in the literature (2015) took place in Poland with the aim of testing the viability of UCG operation in a section of an operational coal mine [15]. The results of the 60-day trial demonstrated the feasibility of this approach but found that the moderate gas production rates and the quality of the syngas produced fell short of what would be required for commercial exploitation in the near term. Further details on this trial in the Wieczorek mine are provided by Piotr Mocek *et al.* [17]. The work described is a follow-on to earlier trials in China in both abandoned and active coal mines in which existing mine shafts and galleries were used to carry the oxidant pipeline to the UCG location and to carry the syngas product pipeline. The trial was conducted at a coal seam depth of 460m using a number of oxidants in succession (air, oxygen-enriched air, CO₂). As part of the safety regime in this active mine, the gasification had to be conducted at a slight negative pressure to avoid the risk of product gas escape into the mine workings. The published results include a heat and mass balance and demonstrate that stable operation was obtained. However, the safety requirement to keep the gasification pressure low resulted in

a syngas composition that would be suitable only for combustion in a power generation unit rather than the wider range of syngas applications targeted by others. They also conclude that pressure control is critical in an operating mine environment, and advocate the operation of multiple, parallel gasification chambers to improve the stability of gas composition.

A recent paper on UCG modelling draws upon many of the concepts outlined above [18]. It is based on the CRIP approach to UCG (Controlled Retractable Injection Point) that has dominated the most recent large-scale UCG trials in the US, Canada and Australia [15]. The paper describes many of the inter-related processes taking place during UCG (combustion, pyrolysis, gasification, heat transfer, physical deformation, spalling, *etc.*) and points to a number of modelling exercises carried out during the period 2014 to 2021 [18]. It then goes on to describe the development of a model for a particular location at the Shanjiaoshu coal mine in China. The model sets out to cover the ignition process (based on electrical heating to reach the ignition point of coal), the initial gasification (based on ten interlinked chemical reactions), the establishment of a temperature gradient in the surrounding strata due to conduction and convection, the outward growth of the cavity, and the effect of regularly retracting the injection point. Broadly speaking, it consists of a thermodynamic and heat flux model in which the injection point is regularly displaced, coupled (two-way) with a thermomechanical model of the coal and rock strata. Simplifying assumptions are made in the interests of computational feasibility: for example, roof and floor rock strata and the coal seam are homogeneous and continuous; the rock surrounding the gasification channel is homogeneous and thermal conduction within it is isotropic; the cross section of the gasification cavity is fixed and rectangular; and stress-strain relationships are linear-elastic. The model predicts and quantifies a cavity growth pattern which aligns with the teardrop shape familiar from earlier field experiments, and surface effects (from sagging of overlying strata) that are broadly in line with experience, and the authors plan to do further work on it.

UCG trials over the years have demonstrated that the composition of the gas mixture produced is affected by the presence of water (either flowing into the UCG cavity from the surrounding strata or injected as a gasifying agent), the presence of CO₂ (whether produced in the combustion zone of the cavity or injected as a gasification agent), the presence of certain minerals (such as calcite and kaolinite), as well as commonly adjusted parameters such as operating temperature, pressure and extent of oxygen enrichment. A recent paper by Fan Zhang *et al.* reviews the state of knowledge of the above and then sets out to quantify the effects with particular reference to deep UCG (>2,200 m) [19]. Deep UCG is a topic of increasing interest in China, partly because

depths in excess of 800 m offer an opportunity for the storage of captured CO₂, and partly because the risk to potable aquifers and other environmentally sensitive areas is lower, but mainly because much of China's extensive coal resource is at depths where conventional mining is difficult in terms of economics and safety [19]. At greater depths, both water and CO₂ are present in their supercritical forms (transitioning at 374.3 °C/22.1 MPa for water and 31.1 °C/7.38 MPa for CO₂), which significantly affects their properties. The experimental approach was to grind the coal samples, mix in the minerals of interest, add them to an autoclave with controlled amounts of water and CO₂, take the autoclave up to the target conditions of temperature and pressure for 30 minutes, and then analyse the gases produced. In this way, all of the variables of interest could be altered independently over a series of experiments. In order to explore beyond the design limits of the experimental autoclave (700 °C, 28 MPa), extrapolation and simulation was used based on the Gibbs free energy minimisation method [19]. Their main conclusions relate to the quantification of the increase in yields of hydrogen and methane that come from CO₂ addition, the effect of higher water levels (more hydrogen; less methane), and the catalytic effect of calcite. Reaction temperature, as expected, also has a significant effect.

A recent paper examines the case for deep UCG optimised for hydrogen production in China (using the term 'deep IGCTH'—*in-situ* gasification of coal to hydrogen) from the perspectives of economics and effective resource utilisation [20]. More specifically, it looks at UCG at a depth of 1,000 m using the CRIP approach (based on data from the 2011 Swan Hills trial in Canada) compared with the established surface gasification option of a Lurgi fixed-bed coal gasifier. In both cases provision is made for an Air Separation Unit (to provide oxygen), a Water Gas Shift unit (to convert CO into hydrogen), an Acid Gas Removal unit (to absorb CO₂), a Pressure Swing Absorber (to separate Hydrogen from Methane), and a Steam Methane Reformer (to convert Methane into Hydrogen). The other competitive routes considered are coke oven gas to hydrogen and steam methane reforming of natural gas to hydrogen with the necessary levels of gas processing to produce an equivalent hydrogen product—all at the same production scale. The aim of the work was to compare these four routes to hydrogen and also to identify the theoretical scope for process improvement in each case within the Laws of Thermodynamics. All of this is aimed at informing decisions about future policy directions and selection of areas for further work. The paper reviews a number of existing comparative assessments in the field of interest and then adopts an advanced exergy analysis approach which also takes account of the energy aspects of the construction phase of energy conversion facilities. The conclusions are: the deep UCG process has an efficiency advantage over surface gasification which increases with scale of production; deep UCG offers a Capital cost and operating cost advantage over surface gasification; there is scope for

further improvement within the gasification units themselves (both surface and underground) and in the integration of the steam methane reforming unit; deep UCG is competitive against the coke oven gas route at the scale considered; and the cost of emissions reduction is lower for deep UCG than for surface gasification if the target is 80% CO₂ capture or higher. The paper also calculates a figure for the rate of Carbon tax that would be required to incentivise the inclusion of CCS with 80% CO₂ capture.

In summary, the UCG field which appeared to be on the brink of commercialisation when Professor Paul Younger was active in it has been going through a quiescent period. Such a pattern of successively high and low activity is consistent with the hundred-year history of UCG. In the meantime, research work continues—laboratory work and modelling—to help underpin the fundamentals and address prospective issues. Chinese researchers are particularly active in the field.

3. Progress with CCS

In the specific field of UCG-CCS, in addition to the various activities and findings cited above under UCG progress, there is a recent paper by Wei Li *et al.* which investigates the safety aspects [21]. This paper cites some of Professor Younger's work on caprock behaviour, formation of a hydraulic seal above the UCG cavity, borehole casing integrity and management of groundwater [6,22,23]. The paper reviews previous work on propagation of fractures in overlying strata in both conventional coal mining and UCG, on physical CO₂ adsorption capacity of post-UCG coal, on the tendency for thermal cracks in the overlying strata to close over time following UCG, and on methods of risk assessment for CO₂ leakage. The focus of Wei's paper is on the effect of supercritical CO₂ injection on fracture diffusion and on the stability of the overlying rock layer [21]. Wei concludes that the primary risk of CO₂ leakage comes from fracture propagation in the overlying strata due to inadequate design. Through theoretical analysis (principally using Darcy's law of multiphase flow) and numerical simulation (using a FLAC3D model applied to a geological sequence associated with UCG), it verifies the feasibility of UCG-CCS from a geological perspective subject to limitations on CO₂ injection pressure, a maximum allowed width of individual UCG cavities which depends on the vertical proximity of the nearest aquifer, and a minimum width of residual coal left in place.

Turning to the broader field of CCS as a whole, compared with the field of UCG this topic has seen extensive programmes of research over recent years, demonstration projects are underway, and pathways to commercial development are at an encouraging stage. To attempt a comprehensive review of developments in the CCS field would be beyond the scope of this paper, but the reader is referred in the first

instance to the large body of knowledge that has been collated and made publicly available by the UK CCS Research Centre [24]. Created in 2012, it has more than 300 academic members who collaborate with CCS organisations across the world, aiming to align CCS research with business needs. They implemented 27 projects in their first 5 years and 24 projects in their second 5 years, and have MOUs in place with CCS organisations in Australia, Canada, China, the Netherlands, South Korea and the USA, and have key relationships with organisations in Norway and Japan. To give a flavour of the pace of development, some key points from their 2024 Spring Conference are quoted below.

The Global CCS Institute report that as of July 2023 there were 41 CCS facilities in operation around the world (capturing 49 Mte/year of CO₂) with 392 CCS facilities in the pipeline (expected to capture 361 Mte/year of CO₂) [25]. There is strong growth in North America, and there are over a hundred CCS facilities under development in Europe [25].

The UK's Department for Energy Security & Net Zero has asserted that "CCUS is a necessity, not an option", pointing to plans for 90 projects which between them have the capacity to handle 94 Mte/year of CO₂ (in a country that currently emits around 450 Mte/year) [26]. The first eight projects have been announced, organised into an East Coast cluster on one side of the country and a Hynet cluster on the other. They estimate that £1bn has been invested to-date in CO₂ capture projects and cluster development, and anticipate £40bn of industrial investment by 2030. Development is expected to proceed in three phases: a market creation phase to 2030 with high levels of Government support; a market transition phase from 2030 to 2035 with reduced levels of Government support; and a self-sustaining phase from 2035 onwards with low levels of Government support [26].

Within the East Coast Cluster, the Northern Endurance Partnership is developing CO₂ storage facilities in the Endurance field linked by pipelines (145 km to Teesside; 103 km to Humberside) to connect with various Bioenergy CCS facilities, industrial carbon capture facilities, power projects and hydrogen projects, spanning 15 companies on Teesside and 12 companies on Humberside [27]. The aim is to capture and store 4 Mte/year from the end of 2027, 10 Mte/year from 2030, and ultimately 23 Mte/year. The saline aquifers being targeted have an estimated total CO₂ storage capacity of 450 Mte [27]. They lie at depths of 1,000m in sandstone formations, sealed by claystones, halite, shales and anhydrite [28].

4. Paul Younger's Legacy

The demand for coal in Western countries has fallen significantly since the time when Professor Younger was working on UCG-CCS, although it continues to grow elsewhere. According to the International Energy

Agency, global demand for coal grew by 2.6% in 2023 to reach an all-time high of 8.7 billion tonnes [29]. They expect global demand in 2024 and 2025 to remain flat. They note that China produces half of the world's coal and consumes 56% of the world's coal, with Asia as a whole consuming 80% [29]. It is notable that most of the recent publications cited in the present paper are by Chinese researchers. The UK picture is in line with most Western countries, with demand (which peaked at 71.4 Mte in 2006) falling to 51.3 Mte in 2010 (when Professor Younger was publishing his work) and down to 4.5 Mte in 2023 [30].

Sentiment in Western countries has turned against coal in recent years (as exemplified by the closure of the UK's last remaining coal-fired power station in September 2024), largely because the unabated combustion of coal (viz. without CCS) is so heavily implicated in climate change. One can only speculate about whether earlier commercial deployment of CCS would have changed all that, or whether the recent acceleration of developments in CCS will trigger a reassessment of coal's place in the energy mix. Another variable is natural gas price since UCG can offer an alternative. The wholesale price of natural gas in the UK today (93 pence per therm, equivalent to £27 per kWh) is about 30% higher than in 2010 when Professor Younger published his work, but at the peak of the energy crisis in 2022 it was nine times higher (£6.40 per therm, equivalent to £188 per kWh) [31].

In the meantime, most of the UCG and UCG-CCS research that is reported is being conducted by Chinese researchers, and (as noted above) Professor Younger's work is being cited by them. Much of the present work is aimed at underpinning the fundamentals of UCG(-CCS) using theoretical and numerical models and laboratory experiments rather than large-scale demonstration projects. Professor Younger always described himself as primarily a field researcher, adding (in his usual self-deprecating manner) that "I'm so clumsy that no-one would trust me in a laboratory". He would doubtless be pleased to see that in countries where coal consumption is expected to continue for many decades, people are following through on some of his ideas for UCG-CSS. He would also probably hold out some hope that once the technology has seen further development elsewhere, the stars might once again align in the UK for harnessing the country's vast sub-sea coal resources in a genuinely environmentally benign manner with widespread public support.

5. Concluding Remarks

Compared with programmes of large-scale UCG field trials and pre-commercial pilot plant developments—the environment in which Professor Paul Younger was working—work in recent years has focused on underpinning key aspects of UCG understanding through modelling

and laboratory work. In this way, advances have been made in understanding how to avoid aquifer contamination and how to predict the manner in which complex networks of UCG channels will grow. In stark contrast with this rather modest progress in UCG, development of CCS technology has been extensive and is on a pathway to commercialisation, although the role of UCG cavities as storage repositories is not prominent compared with the the dominant solution of saline aquifers. In the opinion of the present author, any imminent commercialisation of CCS is likely to have come too late for UCG in those developed countries where there has been a strong groundswell of opposition to all use of coal in recent years. Meanwhile, interest in UCG continues in countries such as China where coal resource greatly outstrips oil and gas resource, and where much of the coal resource lies at such a depth that it would normally be considered to be unmineable. There is growing pressure on such countries to find ways of reducing their greenhouse gas emissions, and one of the responses to that pressure is to consider adopting CCS in some form. It is the present author's hope that any support for deploying UCG at scale will come with a requirement for CCS.

Supplementary Materials

The following supplementary materials are available on the website of this paper: [GES2404040006SupplementaryMaterials.zip](#).

UCG-CCS Introduction.

Competing Interests

The author has declared that no competing interests exist.

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