ORIGINAL ARTICLE

Interdisciplinary studies on the technical and economic feasibility of deep underground coal gasification with CO₂ storage in bulgaria

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Abstract This paper presents the outcome of a feasibility study on underground coal gasification (UCG) combined with direct carbon dioxide (CO₂) capture and storage (CCS) at a selected site in Bulgaria with deep coal seams (>1,200 m). A series of state-of-the-art geological, geo-mechanical, hydrogeological and computational models supported by experimental tests and techno-economical assessments have been developed for the evaluation of UCG-CCS schemes. Research efforts have been focused on the development of site selection

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requirements for UCG-CCS, estimation of CO_2 storage volumes, review of the practical engineering requirements for developing a commercial UCG-CCS storage site, consideration of drilling and completion issues, and assessments of economic feasibility and environmental impacts of the scheme. In addition, the risks of subsidence and groundwater contamination have been assessed in order to pave the way for a full-scale trial and commercial applications. The current research confirms that cleaner and cheaper energy with reduced emissions can be achieved and the economics are competitive in the future European energy market. However the current research has established that rigorous design and monitor schemes are essential for productivity and safety and the minimisation of the potential environmental impacts. A platform has been established serving to inform policy-makers and aiding strategies devised to alleviate local and global impacts on climate change, while ensuring that energy resources are optimally harnessed.

1 Introduction

UCG is an in-situ process of coal extraction and conversion which is conducted between two wells drilled into the seam, one for injecting gasifying agents (air, oxygen or steam) to the reaction zone, and the other to extract the produced gases via the production well. This process develops cavities and the roof will collapse, resulting in further growth of the cavity. Once the quality of product gas has declined in the reaction zone, new coal is exposed by moving the injection point and the process continues until the length of the borehole is exhausted. The size of the cavity formed during UCG impacts directly on economic and environmental factors.

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Reuse of the cavity and surrounding stressed areas of coal for the storage of carbon dioxide (CO_2) is an ideal solution for reducing CO_2 emissions. UCG is rapidly becoming a viable commercial activity in Australia, South Africa and China, while many Eastern European countries are intensively working for its commercialization (e.g. Poland and Hungary).

At the pilot scale UCG has been successfully implemented in countries such as former Soviet Union, Australia and United States (U.S.). Although trial operations of UCG began in the 1930's (Zamzow 2010), the capture and sequestration of CO_2 as an integral part of the operation has only been considered in recent years. UCG-CCS entails injecting and storing the CO_2 produced by stripping the synthetic product gas. CO_2 is produced as a by-product of the shift reaction in which the carbon monoxide (CO) in the extracted synthetic gas is reacted with steam to produce hydrogen and CO_2 as a by-product. Aside from the benefit of injecting the separated CO_2 into adjacent coal seams, the UCG cavities, boreholes and created fractures could provide an additional capacity for CO_2 storage (Pei et al. 2010). Case studies of the potential for UCG-CCS storage have been carried out in the Powder River basin of Wyoming, U.S. (Shafirovich and Varma 2009, Zamzow 2010) and the Williston basin, North Dakota, U.S. (Pei et al. 2010). In Europe, a consortium funded by the European Union (EU) has carried out a pilot investigation of in-situ hydrogen production incorporating UCG-CO_2 management (Rogut 2008, Zamzow 2010).

This project evaluates the potential of deep lying coal seams (>1,200 m) for the development of UCG and the subsequent sequestration of CO_2 in the affected areas, i.e. the abandoned UCG cavity itself, the adjacent stressed coal or the overlying/underlying strata using the same borehole infrastructure with technical modification. The key objectives were to investigate the factors that determine the technical suitability, environmental and economic feasibility of the scheme and to demonstrate that the deep lying coal fields of the target area have the potential for deep UCG and are suitable for both energy production and CO_2 storage using the same drilling infrastructure. If favourable, a future field test of the scheme with industry will be recommended.

State-of-the-art geological, geo-mechanical, hydro-geological and coupled thermo-mechanical models were developed to better understand the UCG-CO_2 storage processes and aid the determination of site selection requirements for evaluation of deep coal locations in the specific site in Bulgaria and elsewhere. The practical engineering requirements for developing the scheme and its environmental and economic benefits were also assessed.

The work covered the following: the development of a geological model for the selected site in Bulgaria; the development of geo-mechanical and cavity models for UCG-CCS; the

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development of a hydro-geological model of the study area; engineering, drilling and completion requirements for UCG and CO_2 storage; environmental assessment of UCG-CO_2 storage; economic assessment of UCG-CCS. The non-technical part of the study included the review of regulatory requirements and an assessment of the overall feasibility of the process; and a research management process that strategised and harnessed results from the individual modules towards the overall aim of the research.

2 Technical assessment

2.1 Modelling the UCG process

2.1.1 Site investigation and construction of geological models

A complete survey of the existing geological information about the target area was undertaken. Digitising the data and re-processing well log correlation led to renewed insights into the spatial behaviour and geometric characteristics of the different formations, and laid the basis for the further modelling and mapping of data for the subsequent geo-technical and hydrogeological modelling of the study.

Using specialised digitising software, all coal seams of the main formations were identified and basic structural and thickness maps and cross-sections were prepared. The coal properties of the different seams were studied (e.g. ash content (A), volatiles (Vs), sulphur (S) and moisture content (W). Coal resources of the seams were calculated from seam thickness and actual surface area).

Structural and tectonic research was undertaken for the purpose of fault modelling – the existing tectonic units were identified and studied, and the bedding angle of the faults was calculated. Using up-to-date modelling software (Petrel software product), a 3D tectonic model for the deposit was developed by pillar gridding method (Fig. 1a), as well as a 3-D interpretative geological model (Fig. 1b). The latter included the creation of the key horizons of the model (*e.g.* the top formation, erosion surface and top Mesozoic aquifer) followed by a 3-D grid editing and zone creation. An investigation of the cap rocks in the upper carboniferous sediments showed that the top formation (of all coal bearing formations) had no effect on the UCG process.

The developed 3-D interpretative tectonic and geological models for the study area improved the understanding of the geological structure of the deposit and the geo-mechanical,
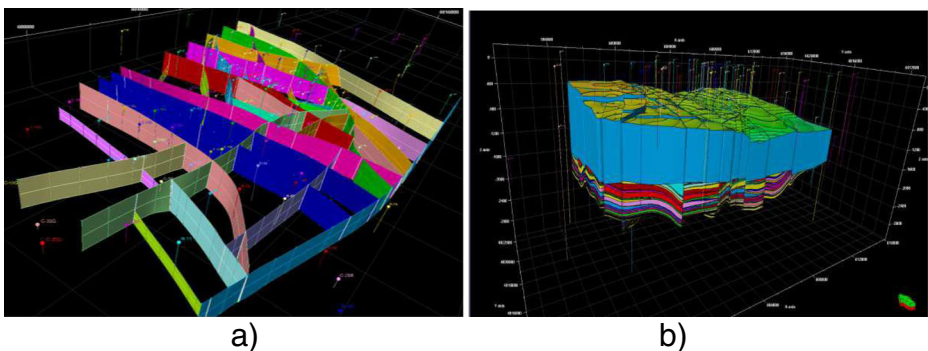

Fig. 1 **a** a 3D view of the fault structure, and **b** the geological model of the study area

hydro-geological and environmental data pertaining to it. The models were a crucial part of the work on assessing the feasibility of the UCG-CCS process for the deep lying coals of the study area and the modelling results were used for the development of the other state-of-the-art models and further assessment.

The study confirmed that the study area has a complicated tectonic structure. Major faults (Triassic age) have been identified around the target area, and while these can be avoided, little is known about any minor faults that exist in the horsts between them. A 3D seismic survey around the target should resolve the structure to within 1–5 m, which is less than seam thickness and sufficient to confirm the site for a UCG test. Additional coal and rock sampling is also required in order to clarify the conditions of gasification and CO2 injection at the target area.

Taking into account the world experience, some generalised site selection criteria for UCG were developed that were additionally assessed and applied to the case of the study area, (Tables 1, 2, 3 and 4). On the basis of a detailed lithological correlation, two sites were chosen that best satisfied the UCG site selection criteria (selected also in a way that would not cause settlements on the surface). Tables 1, 2, 3 and 4 were formulated based on results from geological, geo-mechanical, hydro-geological, environmental, economic and drilling models developed as part of this feasibility study. Some of these criteria are also supported by general knowledge from previous and common practices.

The preliminary results identified the study sites which were bounded by faults and had the best potential for UCG-CCS. The selected coal seams associated with them were between 1,100 m and 1,500 m deep and contained a total of over 75 MT of UCG compliant coal. In order to minimise the influence of the UCG process on the overburden rocks and overlying coal seams, the coal seams were selected on the rule of thumb that the mimimum separation should be ten times the lower seam thickness distance to the upper coal seam' (Healy and Head 1984). Cavities created by UCG activities are much smaller than in conventional mining and accordingly the impact will always be less.

The coal seams were also chosen for the best quantitative and qualitative characteristics suitable for UCG such as low moisture content, density (<2 g/cm^3) low content of sulphur and low coal porosity. The data concerning the sites and the coal seams had been incorporated from additional studies and calculations which are described below.

2.1.2 Modelling of the geomechanical and thermal effect of the UCG and CO$_2$ storage processes

For the purpose of thermo-geomechanical investigation, the first coal seam to gasify is the thickest coal seam in the sequence, which is a seam approximately 10 m thick, located at a distance of 1,500 m below ground level (Overgas Inc. 2011). Finite element software package

Table 1 Coal seam bedding depth in the study area in terms of its suitability for UCG

Depth, m	Suitability
<1200	Not suitable
1200-1500	Highly suitable
1500-1800	Medium level of suitability
>1800	Low level of suitability

Table 2 Coal seam thickness in terms of its suitability for UCG

Seam thickness, m	Suitability
< 2	Not suitable
2-4	Medium level of suitability
4-8	Highly suitable
8-12	Medium level of suitability
> 12	Low level of suitability

ABAQUS was used for the thermo-geomechanical modelling. To represent the geologic faults, the surfaces of both sides of the fault were constrained by a "*contact*" feature in ABAQUS, in which the coefficient of friction between the two surfaces of the fault was assumed constant and equal to 0.2. The ignition line and channel were placed at 2m above the bed of the coal seam studied (i.e. 1498 m below ground).

The material properties were calculated approximately by averaging the individual rock properties with the corresponding thickness fraction of each geologic section. A detailed library of mechanical and thermal properties of coal and rocks under the effect of heat was established from literature references. Details of the ABAQUS modelling and the laboratory tests are given in (Yang et al. 2013). The temperature distributions after ignition, captured every 6 h during 1 day of the gasification process, are shown in Fig. 2. The thermal affected area increase for each time increment and, the temperature is found to be extremely high in the area nearby the ignition centre due to constant heat flux applied at this point. From the literature, (Couch 2009), coal would be pyrolized at a temperature around 400 °C, so to maintain the heat transfer and model integrity elements with a temperature larger than 400 °C heat transfer from the element was allowed. However, in order to realistically represent the mechanical failure of coal after gasification, the elastic modulus of coal was gradually decreased with temperature.

Figure 3 illustrates the temperature distribution for a period of 3 days after ignition, combining view cuts in the X-Y and Y-Z planes to create a 3D view. As expected, when the

Table 3 Thickness of the rocks and their filtration properties

Filtration coefficient, m/d	Thickness of overlaying rocks, m				
	> 200	100-200	50-100	20-50	< 20
< 1×10⁻⁸	Optimum	Optimum	Optimum	Possible optimum	Risk
1×10⁻⁸	Optimum	Optimum	Possible optimum	Risk	High risk
1×10⁻⁶ – 1×10⁻⁴	Optimum	Possible optimum	Risk	High risk	Inappropriate
1×10⁻⁴ – 1×10⁻¹	Possible optimum	Risk	High risk	Inappropriate	Inappropriate
> 1×10⁻¹	Risk	High risk	Inappropriate	Inappropriate	Inappropriate

Colour index	Suitability
	Optimum
	Possible optimum
	Risk
	High risk
	Inappropriate

Table 4 Reflectivity of vitrinite in the study area in terms of coal suitability for UCG

Reflectivity of vitrinite, %	Suitability
0,2 – 0,5	Medium level of suitability
0,5 – 0,8	Highly suitable
0,8 – 1,0	Medium level of suitability
1,0 – 1,5	Low level of suitability
> 1,5	Not suitable

ignition point is moved, the position with the highest temperature changes accordingly. The highest temperature as well as the overall thermal affected area is increased gradually. The surface subsidence after gasification is shown in Fig. 4. Since a geologic fault is included in the model, the subsidence curve is not smooth and there is an obvious jump at the location of the fault. Also, from the results, it was found that as the ignition process is taking place, the surface subsidence is slightly increased. The maximum surface subsidence is approximately 0.025 mm after the first day of the gasification and 0.08 mm after the third day of the gasification.

The 3D coupled thermal-mechanical models provide a detailed analysis of the UCG process in terms of heat transfer, cavity growth and surface subsidence. The 3D models incorporated the real lithological structure from the site and the thermal-dependent material properties from experiments and literature references (Kim 1983, Lee et al. 1986) to simulate the real time gasification process. The modelling results showed that a minimum distance of 150 m should be kept between the gasification channels and the nearby faults in the site to avoid risky geologic interaction which could lead to potential gas or CO_2 leakage.

The developed 3D ABAQUS numerical model was further extended in order to investigate the faults' behavior, the stresses and permeability in strata around the UCG cavities, the possible roof collapse as well as the CO_2 storage capacity of the selected site. The model incorporated a detailed geologic structure of the site including the positions and depths of the faults as well as the thickness of the coal seam and depth of the coal seam, as shown in Fig. 5. A sensitivity analysis on the acceptable cavity distance away from the faults has been assessed by incorporating a series of assessment criteria and assumptions for pressure distribution and other parameters (Fig. 6). It was found that a distance of 150 m away from the fault would also be applicable. It is also calculated that 12.6 million m^3 of cavity volume can be utilized for CO_2 storage for the case of 150 m distance (considering a produced amount of 52.9 Mt CO_2 during UCG and CCGT within 20 years of operation).

2.1.3 Hydro-geological modelling of the selected site

Analysis of archival hydro-geological information about the target sites A detailed analysis of existing archival and published information about the regional and local hydro-geological and geothermal conditions in the study area was conducted (Antonov and Danchev 1980, Bojadgieva et al. 1998, Hristov 1988, Stanev 1970, Yovchev and Riizova 1962). The most informative reference sources were analysed and lithological - stratigraphic data from deep wells located in the Varna Artesian Basin was collected (including data about available hydrogeological parameters). The regional and local geological and hydro-geological
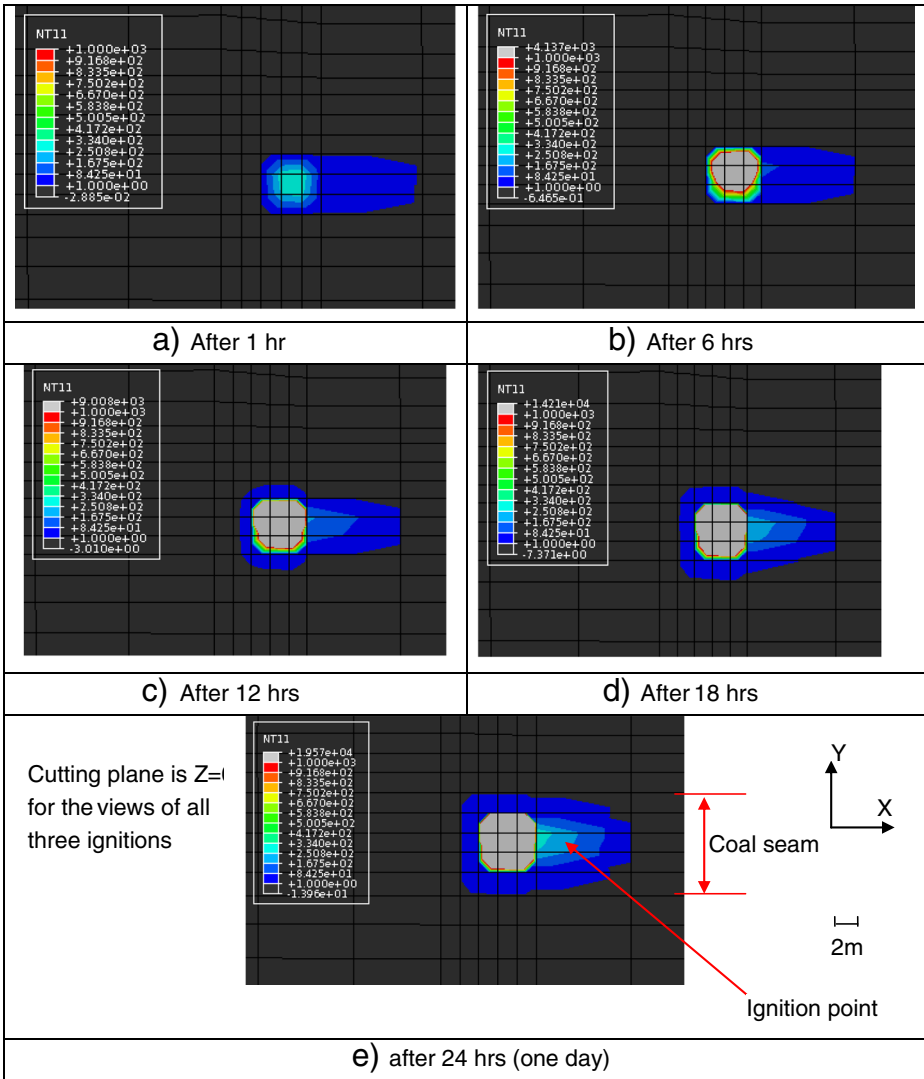
Fig. 2 Transient temperature transfer under the ignition for 1 day Note: NT is the Node Temperature

conditions were clarified for their further utilisation in the conceptual hydrogeological model development. 344 wells in total were examined but only 238 of them provided information on the regional spreading and parameters of hydrogeological units. The regional data provides a large-scale perspective of the regional hydrogeological conditions but not sufficient information about the local site conditions; as a result, the regional data is augmented with additional site-specific data and information specifically for the site-scale hydrogeological model.

The obtained data provided information about the 3D spatial extent of the existing hydro-stratigraphic units, the hydraulic connections between them, their hydraulic properties (average estimates) and the magnitude and direction of hydraulic gradients. A 3D representation of the top surface and maps of isopachytes were drawn up for the main hydrogeological complexes and aquifers in the area (Fig. 7).
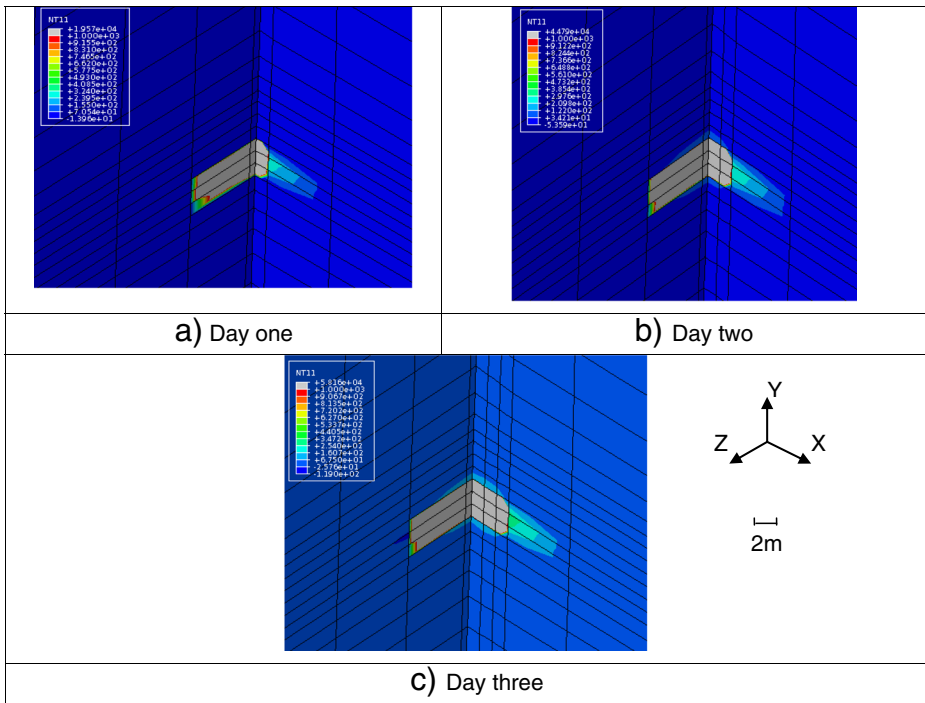
Fig. 3 Temperature distributions under ignition for 3 days (view in 3D X-Y-Z coordinates) Note: NT is the Node Temperature

The best studied water-bearing horizon was that of Upper Jurassic–Lower Cretaceous aquifer. This is the most widely spread and the thickest aquifer in North Bulgaria and has the highest impact on the hydrogeological condition in the study area. The least studied aquifer is the deep Devonian aquifer, which is situated below the Carboniferous coal bearing complex.
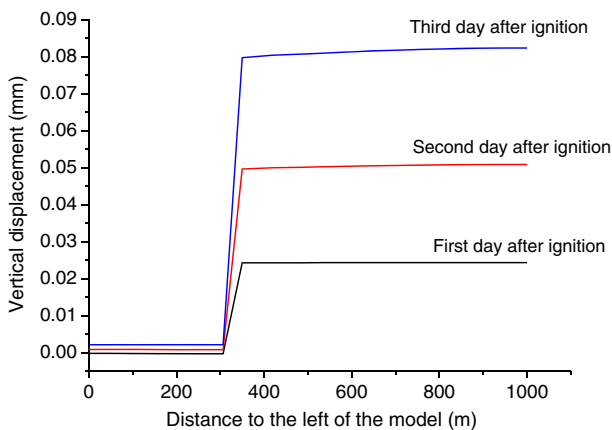

Fig. 4 Surface subsidence across the cross section during UCG for 3 days
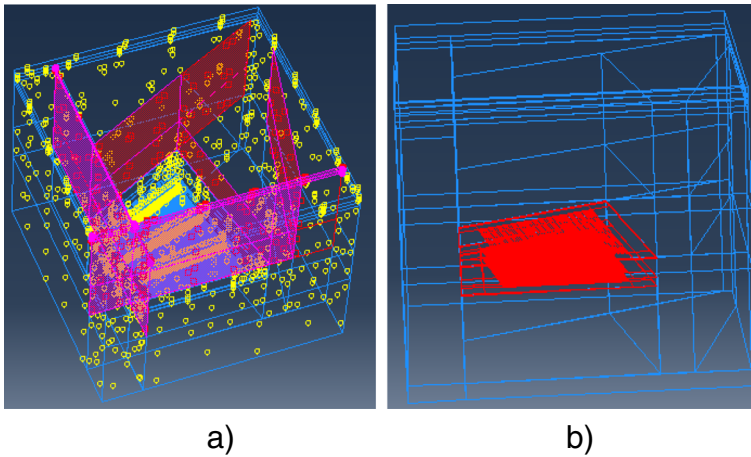
a)   b)

Fig. 5 3-D geomechamical model of the selected site: **a** faults structure in pink and **b** coal seams in red. (small yellow circles are the reference points for the surfaces of the parts)

Groundwater samples taken from different aquifers and complexes showed that the chemical composition of the different water complexes varied considerably. It was mainly influenced by the hydro-geological conditions of the water bearing complexes and less by the depth of formation. Analyses of 27 coal samples from the study area were undertaken. The elemental analysis of coal was conducted by using a Perkin Elmer CHNS/O Analyser. The data was used for the prediction of mineral characterisation of cavities and coal seams for potential CO_2 sites. The main characteristics of the geothermal field of the target area were also studied (e.g. temperature, geothermal gradient, thermal properties of the rocks and heat flow). Data from temperature measurements in a large number of deep wells (over 200) in the study area was obtained and the thermal properties of about 170 rock samples (taken from 10 structural wells) were measured at laboratory conditions (Bojadgieva and Gasharov 2001).

The region of studied coal basin is located close to the Bulgarian Uplift which is a recharge zone for the main aquifers in the north-eastern part of the country. The geothermal field is strongly disturbed by the presence of the Malm-Valanginian aquifer both in vertical and horizontal directions. The hydro geological regime of the Malm-Valanginian in the studied area is closely related to the permeability changes of the built up karst and the small distance to the recharge zone. Negative geothermal gradients are registered within the Malm-Valanginian

Fig. 6 Contact pressure distributions on the faults
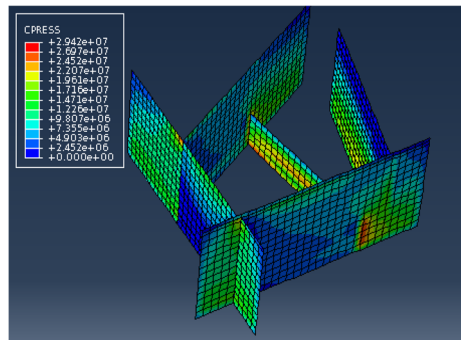
interval in the western and central part of the coal basin and close to zero gradients – in the eastern part. The temperature field distribution in the Carboniferous stratum is presented in Fig. 8. The temperature increases from west to east direction. The zone of lowest temperature is marked between Gurkovo (in the west) and Mogilishte (in the east) and is associated with the intensive cooling taking place in the Malm-Valanginian.

The analysis of hydrogeological and geothermal data allowed fixing of the scope of the regional hydro-geological model. After analysing the uncertainties and possible alternatives, a conceptual model was adopted as a base for the future modelling. The conducted analysis helped to clarify the existing regional and local hydro-geological conditions and to create a conceptual model that served as a base for the further development of regional and local scale numerical models.

Development of regional- and local-scale numerical models of the hydro-geological conditions The developed 3D regional groundwater model represents groundwater flow in the Vranino tectonic block (Fig. 9). The model (Fig. 10) was built using the computer program MODFLOW (Harbaugh et al. 2000, McDonald and Harbaugh 1988). The coalfield is overlaid by several regional aquifers but the most important to be affected by UCG and CCS activities is the Upper Jurassic-Lower Cretaceous aquifer (Malm-Valanginian). This aquifer is the main source of municipal water supply throughout north-eastern Bulgaria, and needs to be protected against both UCG-CSS activities and wellbore leaks.

The UCG produces a range of potential contaminants such as benzene, toluene, phenol, ammonium, sodium and sulphate. Currently, there is a data gap because of limited work on tar and contaminant production during UCG (Burton et al. 2008, Burton et al. 2004), although recent tests have published contaminant compositions. The temperature, pressure, porous media properties, and composition of the liquid and gaseous phases (including contaminant concentrations in the groundwater) in the subsurface after the UCG were some of the key
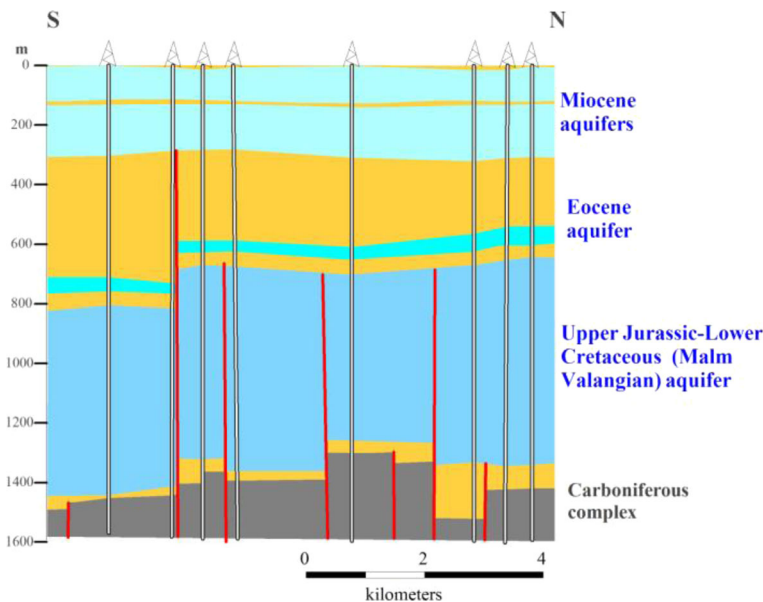

Fig. 7 Schematic hydrogeological cross-section of the main aquifers above the Carboniferous coal bearing complex
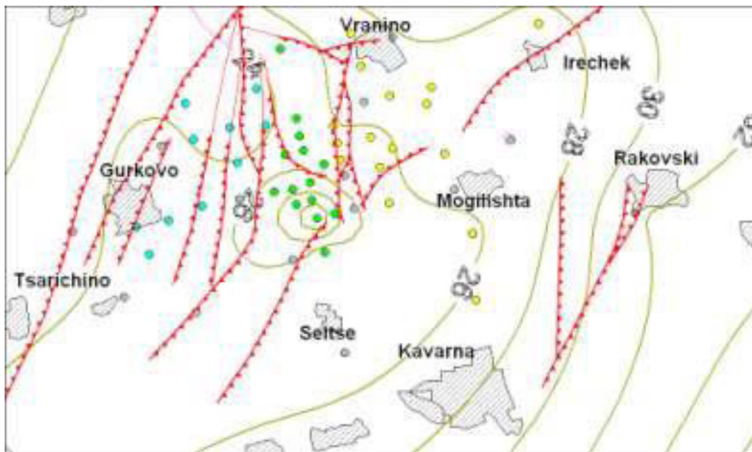
Fig. 8 Temperature distribution at 1500 m below the surface in the studied site (wells are marked by dots)

model parameters addressed by the local numerical model of the test site. These represent the flow and transport of fluids, gases and contaminants in the zone surrounding the study area. The mathematical model was developed using the code FEHM (Finite Element Heat and Mass Transfer) (Los Alamos National Laboratory 2013) allowing for the numerical representation and simulation of all process complexities.

The local-scale model (Fig. 11) accounted for non-isothermal groundwater flow and contaminant transport (benzene was considered to be the primary contaminant of concern).

Feasibility evaluation of UCG and CO$_2$ storage Non-isothermal groundwater flow and contaminant transport was accounted for in the local-scale. Benzene was considered to be the primary contaminant of concern. It was assumed that the gasification of 1 tonne of the study coal would produce about 36 l of coal tar and a relatively small fraction (0.1 %) of that tar would be benzene. Benzene was assumed to be a key contaminant and a 'canary' for potential migration of UCG contaminants in the subsurface environment (due to relatively high production during the in-situ UCG and relatively low detection limits). The highest initial concentration of benzene that could be produced during the in-situ gasification of the studied coal seams would be about 425 ppm assuming a production zone size of $20\times20\times5$ m and porosity approaching 1. This is a conservative estimate that ignores the time it took for the UCG activities to be performed. It is assumed that peak concentration (425 ppm) is instantaneously released at the beginning of the simulation ($t=0$). The volume of the production zone ($20\times20\times5$ m) is assumed to be formed at the end of the UCG activities within the simulated strip ($200\times100\times20$ m). The modelling results showed that contaminant concentrations would exceed 1 ppb after one year of UCG operations but in a relatively small area in the vicinity of the impacted zone. For the later years, the concentrations would be substantially below 1 ppm due to contaminant dilution (Fig. 12).

The physical processes which were accounted for in the numerical model, were fluid, heat and contaminant flow. The contaminant migration was dominated by advection and dispersion. The vertical groundwater flow and contaminant transport between the UCG zones (Gurkovo and Makedonka coal formations) and the Regional aquifer above (the Malm-Valangian formation) was expected to be facilitated by vertical fault zones. The contaminants were assumed to be non-reactive and unaffected by attenuation and decay due to geochemical
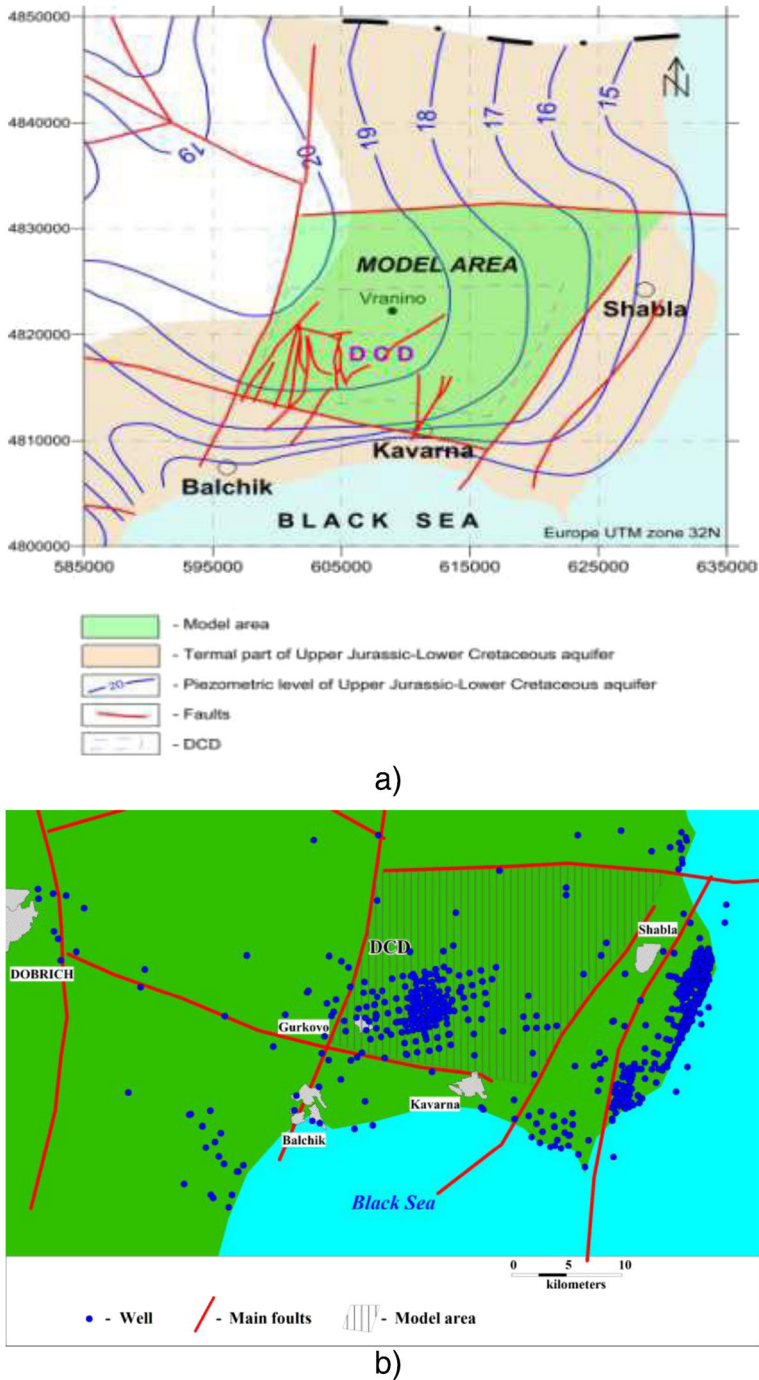
a)

b)

Fig. 9 Location and boundaries of the model domain

processes. The numerical model did not account for potential dissolution of contaminants in the liquid CO_2 phase. The simulations were applied to evaluate the potential for contamination
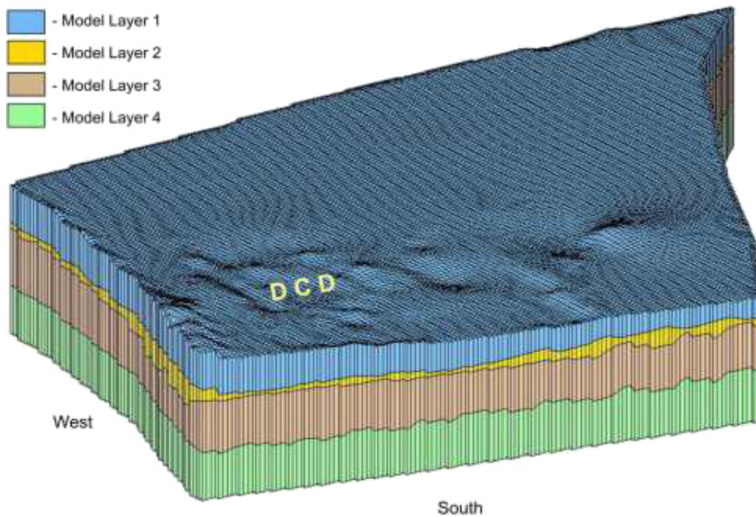
Fig. 10 Spatial distribution of the model layers in the model domain

of the Malm-Valanginian aquifer taking into account uncertainties in the subsurface properties. The models predicting temperature, liquid pressure and flow paths from the Gurkovo formation (bottom) along the vertical fault zone are presented in Fig. 13. The modelling results showed that the heat flow was increasing and the liquid pressures gradient was relatively uniform along the fault due to high vertical hydraulic conductivity.

The developed local-scale numerical hydro-geological model and the performed analyses showed that the UCG-CO_2 storage activities at the studied site would have limited impact on the groundwater quality and would not cause unacceptable environmental impacts on the main aquifer in the region – the Malm-Valangian aquifer. The injected CO_2 mass was predominantly dissolved in the groundwater. The model demonstrated that the performance of UCG and CCS activities at a distance of 100 m from a vertical fault zone with high vertical permeability will not cause unacceptable environmental impacts on the Malm-Valanginian aquifer. A set of criteria for UCG-CCS in the study area is listed in Table 5. They are established criteria from geo-mechanical, cavity and hydro-geological feasibility studies based on conceptual model elements and mechanical/ physical properties of the subsurface.

2.2 Engineering, drilling and completion requirements for UCG and CO_2 storage

2.2.1 Evaluation of technical issues of dual use wells and CO_2 storage in UCG cavities

A comprehensive data base had been established including accessible data from all previous UCG projects in order to identify the most suitable design and to assess the assigned parameters based on coal composition and type of oxidant. It includes detailed historical, technical and chemical information about the UCG process for 81 worldwide UCG projects since 1933 (Couch, 2009). Based on existing literature, this may be the most comprehensive data base of its kind. The analysis of database confirmed that the UCG synthesis gas quality is significantly influenced by parameters such as initial coal composition, oxidant composition, injection pressure and coal seam depth (reservoir pressure). The influence of the UCG
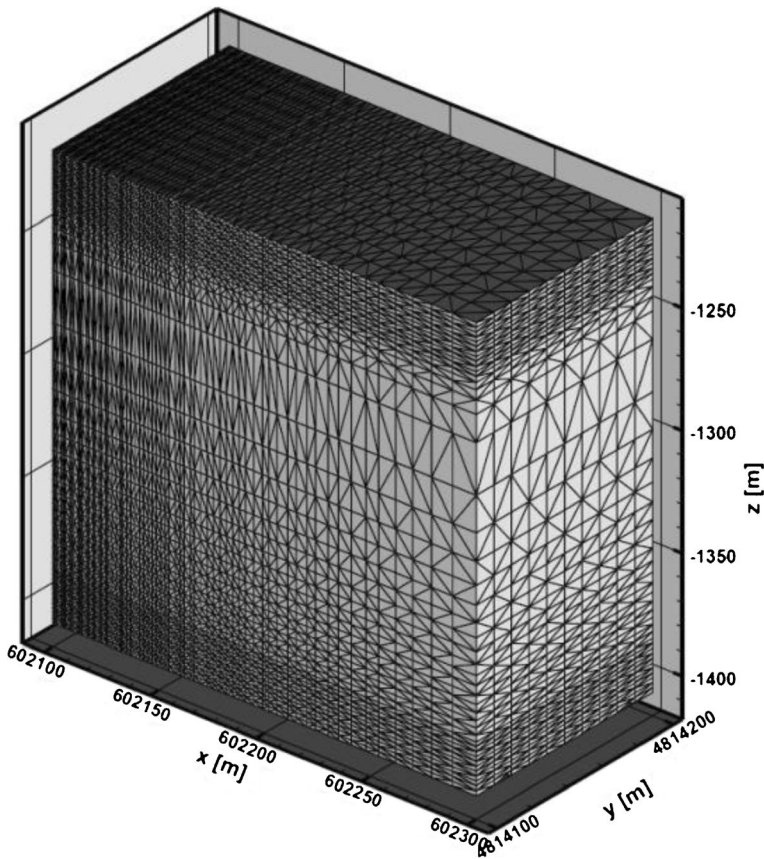
Fig. 11 3D local-scale model setup (model domains with sizes of $200 \times 100 \times 607$ m^3)

technology applied and the oxidiser composition used was observed. Table 6 shows the ranges of some selected parameters within the database. Knowledge of the inter-system relations between the mentioned factors, and consideration of the existing geological data sets of the study area may offer a rough estimate of the resulting synthesis gas composition in the target UCG site.

An assessment of the applicability of reservoir simulators for CO_2 storage in post-UCG cavities was made. Selected simulators should be capable of dealing with non-isothermal or quasi-isothermal conditions, or allow equivalent adaptations to address thermal effects. It would also be beneficial if the simulator can consider the cleat matrix of the coal surrounding the post- UCG reactor. Another aspect of interest is the capability to simulate CO_2 adsorption to coal, coal gasification residues and to surrounding rocks. A review of the state-of-the-art and best practice for CO_2 subsurface injection and permanent storage was also undertaken. Figure 14 gives the generic workflow for a combined UCG-CCS project development.

Deeper coal bed formations (>800 m), potentially suitable for CO_2 storage in Bulgaria occur in two coal fields only. The findings of previous assessments, most notably in the *EU GeoCapacity* project (Georgiev 2008), showed that there is only one Bulgarian coal field with sufficient storage capacity (estimated at 26.2 Mt CO_2). Table 7 shows the current status of
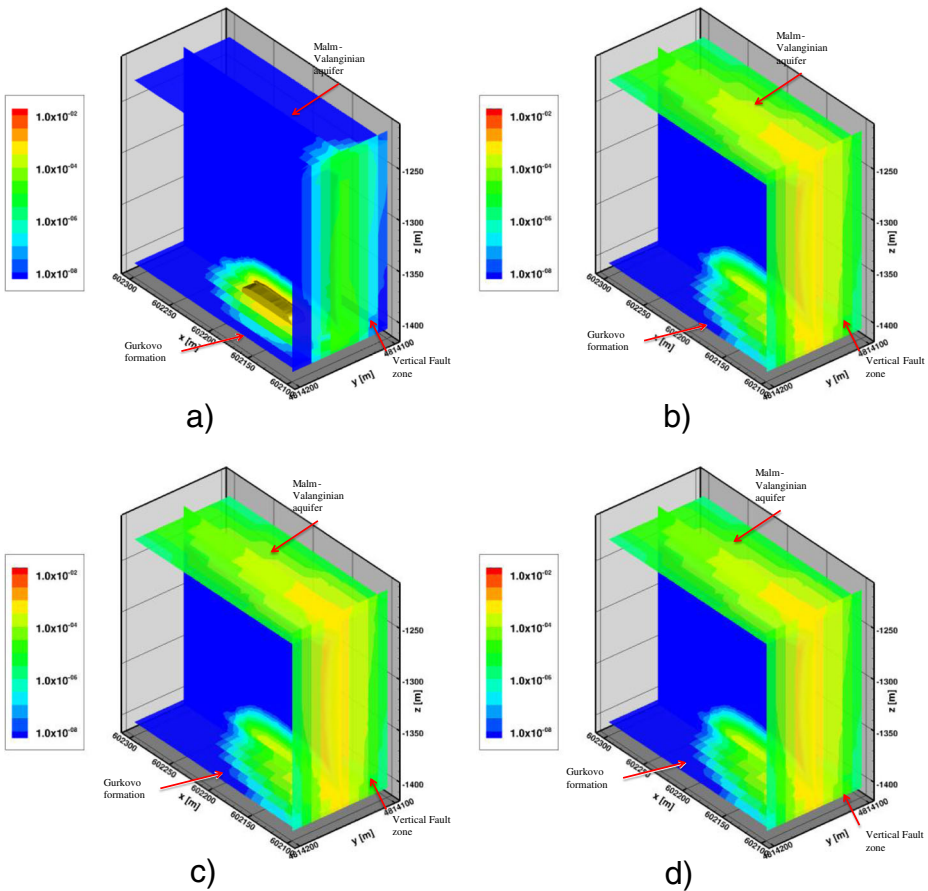
Fig. 12 Model predicted transients in benzene concentrations in ppm. **a** 1 year, **b** 10 years, **c** 100 years and **d** 1000 years after the UCG and CCS activities have been performed

knowledge regarding features required for CO_2 storage and their application for a potential UCG site in the study site.

Directional drilling is a proven technology in the oil and gas industry. When drilling in coal seams or their vicinity, the following additional technical challenges had been found to exist compared to conventional hydrocarbon projects:

– Coal seams are frequently much weaker than the strata surrounding most oil and gas reservoirs. Therefore, mechanical stability of long in-seam holes is an issue. Coal is also sometimes difficult to drill due to its friability. Drilling in coal is a relatively rapid process compared with drilling in harder host rocks.
– Conventional reservoir targets are usually thicker than most coal seams. Seams may be folded, faulted and/or fractured and could be difficult to follow.
– The precision requirements of drilling in a narrow seam are much higher than those for most hydrocarbon projects, although the depth and operating pressure may be lower.
– The fracture network in coal is sensitive to blockage from cement or drilling mud.
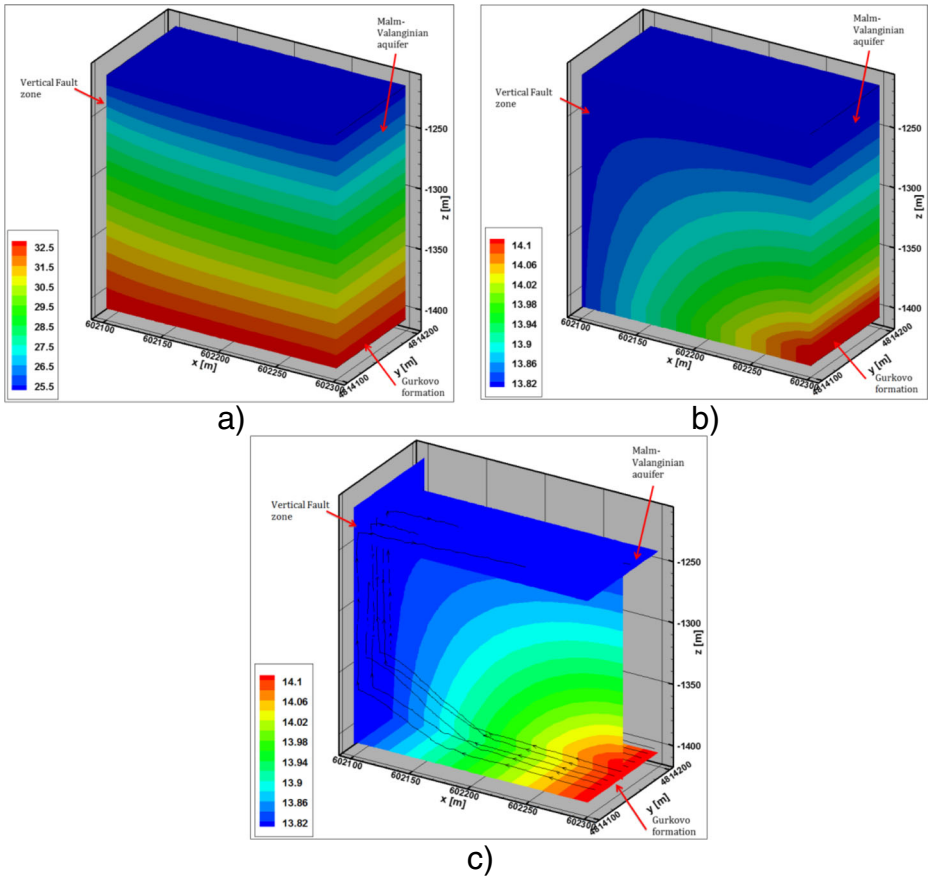
Fig. 13 Simulated steady-state groundwater flow through the model domain for the base case **a** Model predicted temperature (deg C), **b** Model predicted pressure (MPa), **c** Model predicted flow paths along the vertical fault zone

– Downhole casing equipment will be exposed to an aggressive chemical and thermal environment in UCG applications.

The set-up that is likely to be applied to the project would require at least two boreholes for one panel- injection well and production well. The actual panel layout combines a number of injection well branches crossing one deviated production well. It was envisaged that for the CO_2 injection, only the vertical part of the injection well (s) would be used (the horizontal part would not be required because of the cavity development) and low permeability would not be an issue any more.

The combination of conventional drilling of the vertical/caprock section with subsequent coiled tubing (CT) for the build-up and horizontal/in-seam section was addressed as one of the state-of-the-art methodologies. Today in-seam legs of up to 1,000 m can be achieved. The coiled tubing drilling technology allows continuous progress and stabilised hole conditions. The in-seam leg can be stabilised by a liner, also used for the retractable ignition. The trajectory has not only to follow the seam but also to meet the production and/or ignition wells. Exposure of well completion materials to aggressive chemical environment should be

Table 5 List of criteria from hydo-geological investigations

Category	Desired value	Comments
Coal thickness (m)	>2 m	Not greater than 30 m. Ideally 5–10 m
Number of seams to be gasified		Avoid seams with overlying coal within 15 m
Thickness variation (% of seam thickness)	<25	Avoid variable thickness seams
Depth (m)	>92	Preferably more than 300 m and not more than 2000 m
Angle of coal seam (degrees)	0–70	Any but steeper is preferred as it may be technically difficult to mine through conventional methods.
Variation of the angle of the coal seam (% of average angle)	<2	
Thickness discontinuity (m)	1	Avoid seams with variable partings/discontinuities.
Overburden (m)	100	Floor and roof conditions needs to be examined carefully.
Coal rank (vitrinite reflectance)	Low rank bituminous	Free swelling index should be low. Sub bituminous or lower rank, ideally not coking, non-swelling coals.
Ash content (wt %)	<50 %	
Coal sulphur (wt %)	<1	Volatile matter greater than 10 %. Sulphur should be removed along with syngas.
Coal moisture (wt %)	<35	Preferred 7–35 %. Controlled inflows of water or high moisture contents are desirable especially after ignition.
Gross calorific value of coal	>12MJ kg^{-1}	
Thickness of consolidated overburden	>15	
Seam permeability (mD)	50–150	More permeable greater than 20 %. Swelling coals may interrupt the gas circuit. High permeability coals may allow excessive water infiltration causing possible chance of gas leakage and contaminant movement.
Porosity of coal seam	>30 %	Porous coal seam.
Distance to nearest overlying water-bearing unit (m)	100	
Coal aquifer characteristics	Confined	
Available coal resources (106 m3)	>3.5 Mt	>20 years long operation. Depend upon gas utilisation and profitability.
Proximity to faults	>150 m depending on site conditions	If many major faults then site specific calculation required to be carried out for the accurate estimation of the distance.
Distance from active mines (km)	>3.2	
Distance from abandoned mines (km)	>1.6	
Geology-lithology		High UCS, non porous and impermeable strata
Hydrology	Non aquifer strata is preferred.	Non porous strata <30 %, Impermeable <5 %, Moderate water ingress. Avoid potable aquifer and large water bodies.

Table 5 (continued)

Category	Desired value	Comments
Geotechnical strata properties	Rock strength: Uniaxial compressive strength range 50 to 250 MPa. Density greater than 2000 kg/m^3	Avoid excessively fractured, faulted and broken rocks as they may cause water inrush or product gas and contaminant leakage
Infrastructure availability		Roads, electricity and power transmission lines
Presence of coal bed methane		Depends upon economics or commercial value of CBM deposit and its interoperability with UCG.

checked. No significant risk of steel corrosion is expected in wells where CO_2 is injected and maintained in a dry and supercritical state (scCO_2), since the corrosion rate is quite low in the presence of dry CO_2.

With regard to well integrity during UCG-CCS operations, the operational period of a dual-use well is relatively short (two to three years). Taking into account the influence of the UCG process, the performance of materials has to be considered for each stage. Injection rates, pressure, the fluid saturation in the UCG cavity as well as geochemistry, volume, viscosity and content of injectant (s) play an important role in the overall well design. The completion type required to ensure CO_2 injectivity over the entire well life cycle has to meet performance requirements. Certain general and site specific parameters have been adopted as a basis for detailed planning (Table 8). Final closure of the well bore will follow the general rules that have to be applied to all abandoned CO_2 injection wells.

UCG and CO_2 storage are two technologies that have been tested and to some extent already applied commercially. Except for some research and development (R and D) studies, no site test trials have been performed combining those two technologies. Deep sited UCG projects are also relatively rare but the available information on them helped to identify and evaluate technical issues related to UCG and CO_2 storage projects. The preferred set-up of the

Table 6 The ranges of selected parameters

| Parameter	Minimum	Maximum
Average seam depth (m)	15	1,200
Average seam thickness (m)	0.75	18
Seam angle (°)	0	56
Well spacing (m)	10	210
Coal gasified (t)	0.3	2,781,800
Injection (kmol/h)	7	1,223
Injection pressure (kPa)	120	7,500
Production pressure (kPa)	110	1,000
System pressure (kPa)	207	8,000
Total coal wet production (kmol/h)	22	4,860
Coal (dry) heat value [MJ/m3 (dry STP)]	2.57	12.17
Gas recovery (%)	43	110.30
Synthesis gas heat value (MJ/m^3)	2.8	14.60
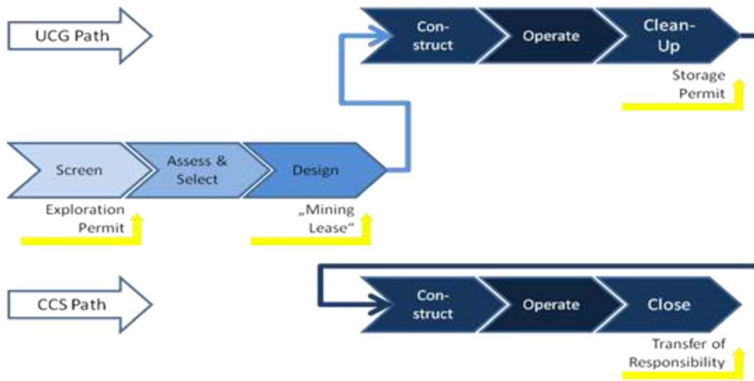
Fig. 14 Generic workflow for a combined UCG-CCS project development (Yellow arrows refer to permits that a project developer may need to acquire during the life of a CCS project.)

most recent UCG projects includes two sub-parallel deviated in-seam wells (for injection and production) and one vertical ignition well (Parallel CRIP).

No detailed research regarding the suitability and feasibility for UCG of the selected coal deposits has been performed and so a preliminary assessment is important. One of the requirements for CO_2 storage is a depth of at least 1000 m in order to allow storage of CO_2 in a dense phase. This demands an adequate gasification depth which is much deeper than the depth of the most recent UCG trials. A greater depth of gasification and storage also reduces the risk of groundwater contamination. Changes in many key parameters with depth will be site-specific but increasing depth increases development and operational costs. Careful site selection and characterisation is the key to success.

The preferred drilling method is a combination of conventional drilling for the vertical/caprock section with subsequent coiled tubing for the build-up and horizontal/in-seam sections. There is however only a small number of drilling companies with respective experience. Considering the costs of drilling and inherent risks in penetrating cap rocks using multiple injection wells, strategies should be considered that involve reducing the overall well count.

Table 7 Features required for CO_2 storage *[based on* Bachu and Adams (2003)]

Features	Dobrudzha Coal Deposit (after UCG)
Appropriate depth	√
Occurrence of potential sealing formations	√
Occurrence of potential reservoir rocks	√
Moderate tectonic deformation	? (to be determined)
Adequate dia-genetic process	? (to be determined)
Effective regional-scale hydrodynamic barriers	? (to be determined)
Favourable flow systems	? (to be determined)
Adequate porosity	√
Adequate permeability, capability for large scale migration, trapping capability	√

2.2.2 Design of a UCG well configuration and its modification for CO$_2$ injection

The design and configuration of wells suitable for a combined UCG and CO$_2$ storage project in the study area was developed, including a workover and development programme for CO$_2$ injection. The design and configuration considered general parameters and adopted some site specific parameters corresponding to the geological conditions in the study area, accounting for the necessary regulatory requirements. The workover and development program examined applicable monitoring technologies -respective experiences were identified from active projects and through a review of previous projects on UCG and CCS. The health and safety, and regulatory implications of dual function wells in a potential deep UCG pilot with subsequent CO$_2$ storage were also examined.

The drilling and completion program for the study area was a recommendation procedure for the preliminary selected geological blocks characterized by the wells. The basic set-up included a vertical section which is cased down to the starting point of the horizontal deflection at a vertical and horizontal distance from the planned entry point into the seam. The final diameter of the injection well depends on the adopted UCG design and the subsequent calculations of incurring gas volume streams. The adopted inner diameters for the injection and production wells (3½"=88.9 mm and 4¾"=120.7 mm respectively) could also be accommodated for a higher volume streams of the oxidising agent, the syngas and the CO$_2$. Optimised diameters should be determined by a detailed cost assessment of seam properties and costs for varying drilling diameter (and quality), compared against increasing costs for purchase and operation of pumps (Nakaten et al. 2013a).

The injection well should be drilled into and along the coal seam, while the production well is drilled perpendicularly such that the production well meets the trajectory of the deviated injection well. The currently proposed layout (Fig. 15) shows the injection wells in red and purple with well sites of the vertical section located in the two corners of the gasification panels. Since every turn reduces the power that can be applied to the drill bit and the loss of

Table 8 Possible post-UCG CO$_2$ storage well design conditions

| Parameter	Dual-use post-UCG injection well	Comments
Fluid type in the UCG cavity	Water, CO$_2$, N$_2$	CO$_2$ in supercritical state
Well design life time	About 10 years	1–3 years UCG and up to 1 year of CO$_2$injection
Design injection rate	1 kg/s	Based on the overall UCG panel design
Bottom hole temperature	About 100°C after UCG cool down	Cool down process time leads to dissolution of contaminants increasing risk of well corrosion
Well head pressure	About 170–220 bar at depths of Macedonka and Gurkovo seam sections	Containment loss has to be avoided in the injection zone by not exceeding a pressure threshold
CO$_2$ purity	95–99.9 % by weight	
Corrosion H$_2$S related and other influence	Exceeding the NACE limits	
H$_2$O	Assumption that dehydration capacity is exceeded during CO$_2$injection process	Related to water back flooding due to shut-ins
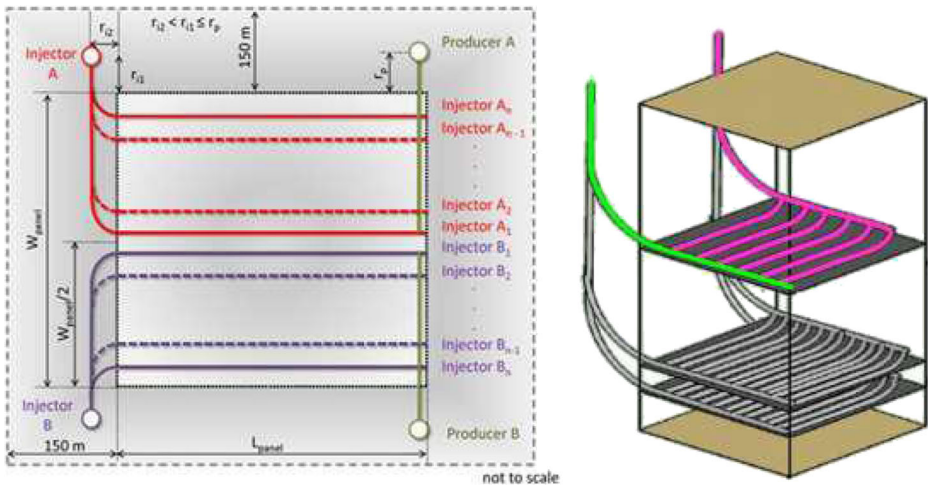
Fig. 15 Proposed panel layout (left: plan view, right: 3D block view, both not to scale) The block view on the right exemplifies one half of the total panel; the other part is symmetrical to this block

torque is greater for narrower radii, the first deviation is planned with a radius r_{i1} greater than r_{i2} but not greater than rp, so as to keep an appropriate distance from the next potential fault (i.e. the geological boundary). The respective build-up rates for the applied diameters are 20° and 60°. The narrow radius for the production wells is quite ambitious for a 4¾" well diameter, while the greater diameter will be in a medium range even for a 6½" well diameter (production well, in green).

A number of in-seam sections will be drilled from a single vertical well, thus, only a limited number of vertical wells will be required. After the completion of the vertical drilling the injection wells should be cased from the surface down to the top of the build-up section. Following build-up and in-seam-drilling, this section is to be lined and the well temporarily capped. The production well is expected to be drilled after the deviated injection well and will be cased all the way to the top of the build-up section. Once "communication" with the respective leg of the injection well is established, a liner should be installed in the well, which should be temporarily capped.

Appropriate shut-down procedures have to be applied when an UCG reactor (the gasification channel or entire UCG panel) is closed down. The main goal is to avoid the escape of toxic UCG by-products and the potential for subsequent contamination of freshwater aquifers. The so called 'clean cavity' concept has been developed and tested within the scope of previous UCG projects. However, the experience with the concept is still very limited and requires further field work and research.

The shutdown of the UCG reactor is undertaken in three steps. The injection of the oxidant is reduced and ultimately stopped. The cool-down process can be supported by injection of water into the cavity (being again converted into steam underground) and its subsequent production (Yang et al. 2013). In the next step the gasification is finally extinguished, hence, any wells not required for further operation may be abandoned according to best practise and national regulations. Finally, the water from the extinguished UCG reactor is recovered by pumping. This process may be repeated until contaminants concentration (mainly the contaminants with high water solubility) is reduced to a degree required by the local regulations on water protection. In case of

low water ingress or a weak aquifer connectivity of the UCG cavity, the clean-up process can be supported by cycling water through the shutdown reactor in order to use it as a solvent for contaminants. After shutdown and cleaning, water quality is monitored with regard to required parameters. If the required national standards at the site are not met, water has to be produced and treated at the surface. Several months/ years may pass between the single operations.

2.2.3 Post-injection management of CO_2 storage in UCG spaces

A best practice guide for the sealing of wells after CO_2 injection was completed. It specifies the general technical terms and requirements (e.g. well design and sealing) needed to assure a safe long-term CO_2 storage and recommended options for long-term monitoring of the cavity, well and storage space. The best practice guide can be used as a tool to determine essential technical terms and monitoring requirements to assure a safe long-term CO_2 storage in compliance with the EU Directive on the geological storage of CO_2. Yet, the process of defining a particular monitoring program for a safe long-term CO_2 storage must always consider the local site-specific (geological) conditions and circumstances.

3 Environmental assessment of UCG-CO_2 storage

3.1 State-of-the-art for the potential for environmental impacts of UCG-CO_2 storage

A detailed study of the state-of-the-art in potential environmental impacts from UCG and UCG associated with CCS was carried out addressing issues including the impact on the groundwater environment, the environmental impact during the transition of the abandoned cavity to equilibrium and CO_2 injection, and the long-term impacts of CO_2 storage in the cavity and the subsequent mineralisation.

3.1.1 UCG impact on the groundwater environment

The risk assessment techniques currently used for groundwater contamination are applicable to the concept of UCG–CCS. Groundwater pollution is likely to be a key element for any successful UCG operation. It is known that a suitable site selection process (where key hydrogeological attributes are compared to assess suitability) with adequate engineering planning and realistic environmental impact assessment (EIA) are required to obtain appropriate authorisations for these endeavours.

In order to evaluate the risk to groundwater presented by both contaminant production and transport mechanisms, a comprehensive evaluation of geological and hydrogeological factors at the site is required. A key parameter of the risk analysis is the regulatory regime concerning groundwater of the particular country. The practical application of the theory together with understanding the expected UCG contamination is essential for the assessment of the risk to groundwater in a deep environment.

Evaluation of the influence of UCG on groundwater covers a number of phases including the following:

– Contaminant migration: potential underground pathways that allow these contaminants to migrate to aquifers that are economically or ecologically significant.

– Human activities and their effect on these potential mechanisms.
– The risk of contaminant migration beyond the permanently unsuitable zone (PUZ) in significant quantities that may cause concern to the regulators.
– The risks of surface activities to groundwater.

3.1.2 Human impact in modifying migration pathways

Human activities can have a large impact on contaminant migration pathways at the site and may cause existing migration pathways to become more permeable and even provide new pathways through which potential contaminants associated with UCG can migrate. The main impacts that need to be considered in terms of contaminant migration are collapse of the UCG reactor, mineral workings and resource extraction activities such as coal bed methane extraction, and deep site investigation boreholes and wells.

3.1.3 Geological and hydro-geological evaluation

In simple terms, the evaluation of geological and hydrogeological characteristics in a typical low risk deep environment requires two main activities: identifying the main potentially transmissive features and links between them that could provide a continuous transmission pathway beyond the PU zone, and determining whether hydro-geological conditions are likely to promote transmission of contaminants through potentially transmissive features. This will need a good understanding of the geology and conceptual hydrogeology at a site, supported by desk study and site investigation data.

A summary of data on study are used for EIA studies include

– Detailed descriptions of the host rocks.
– Data on the permeability and transmissivity of Carboniferous rocks and geological formations within the field deposited above them.
– Data on the chemical composition of carboniferous water and of the aquifers above it.
– Detailed regional hydro-geological information for the Upper Jurassic-Lower Cretaceous aquifer most vulnerable to future underground gasification – such as map of thickness distribution, hydrodynamic map and data on hydraulic geological parameters.

Other required data are

– The role of tectonic disturbances as possible ways of contaminants migration is unclear.
– Information for drawing hydrodynamic maps for Carboniferous and Devonian aquifers.
– The technical condition of preserved wells.

3.1.4 CO_2 storage - environmental impacts related to UCG

CCS is a method of abating atmospheric emissions of CO_2. It is assumed that UCG would leave highly porous cavities and stressed strata in its wake. As these areas cool down, the abandoned cavities would be accessed by directional drilling or through the existing production boreholes. CO_2 would then be injected at high pressure for storage and retention. For permanent CO_2sequestration, the depth and strata conditions must be suitable. The

environmental impact of CO_2 sequestration in a UCG scheme is also affected by the environmental factors considered for the UCG process.

3.2 Development of a mathematical model to assess the environmental sustainability of UCG-CO_2 storage

The main purpose of the UCG process is to obtain a sustainable energy source. This process should be aimed to achieve an adequate balance between financial, environmental and social factors in the energy generation process. As a scientific contribution to an effective sustainable environmental management of the UCG process, an innovative numerical model has been developed (expressed in terms of an Environmental Sustainability Index (ESI)) to quantify the environmental sustainability situation of the "in-situ" UCG process with CO_2 storage. In a given time and space this parameter allows the definition of an environmental sustainability standard or a minimum permissible level of sustainability for future projects. This approach is based on four environmental indicators: (i) atmosphere quality, (ii) rock and soil subsidence, (iii) groundwater quality, and (iv) surface water quality. The main purpose of this index will be the establishment of acceptability criteria for new underground coal gasification projects, as well as optimisation of studies for existing installations.

The developed ESI quantitative model is a function of 4 component indexes: Subsidence Sustainability Index (SSI), Groundwater Sustainability Index (GWSI), Surface Water Sustainability Index (SWSI) and Atmosphere Sustainability Index (ASI). The calculation of these indexes considers the condition of sustainability of each pollutant based on threshold limit values, given by the existing standards.

The basic equation used for the calculation of the Environmental Sustainability Index of UCG/CCS is:

$$ESI_{\frac{UCG}{CCS}} = \frac{1}{4}\left(SSI + GWSI + SWSI + ASI\right) \tag{4}$$

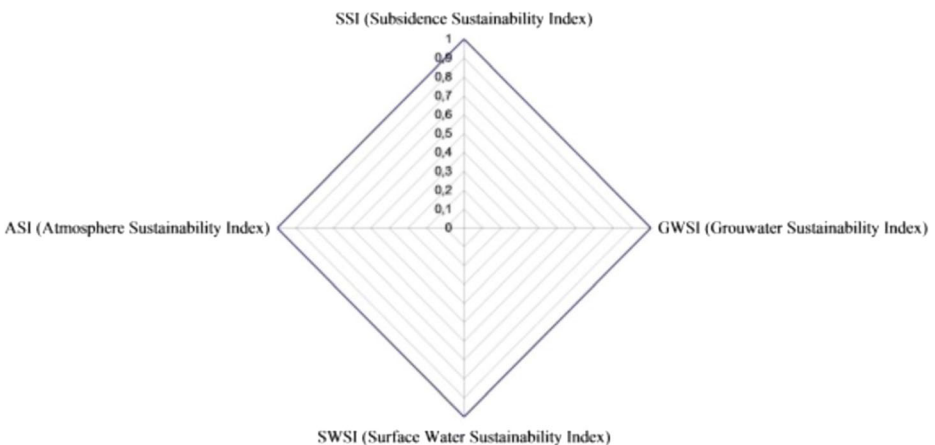The graphic representation of the results is given by Fig. 16.

Fig. 16 Structure of Environmental Sustainability index of UCG
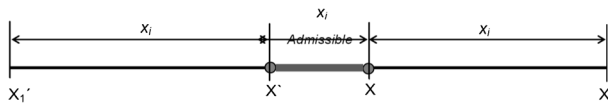
Fig. 17 Sustainability criterion

For the purpose of calculating the sustainability index (SI) of each component (SSI, GWSI, SWSI and ASI), the mathematical model uses the condition of sustainability of each element (X and/or X') based on the standard of sustainability or life quality given for the norms. Three sustainability criteria are taken considering the state of the local environmental conditions (Fig. 17).

Sustainability criterion: $X' \leq x_i \leq X$ are admissible values, $x_i \geq X$ and $x_i = X_1$ are unsustainable values and $x_i \leq X'$ and $x_i = X_1'$ are unsustainable values.

Permissible minimum level of the ESI for UCG and CO_2 storage is proposed (Table 9). As the quality of the 4 environmental indicators (subsidence, groundwater, surface water and atmosphere) vary with time, the ESI for UCG and CO_2 will vary too.

3.3 Application of the developed model to possible coal deposits

The developed ESI model was applied to practical coal deposits, such as the study area in Bulgaria, the Florina basin in Greece and the Spanish coal deposit El Tremedal (Teruel). Real coal data for study area obtained from the study was incorporated in the environmental model, thus improving and enriching the already created basic ESI model. The four environmental indicators (Subsidence Sustainability Index (SSI), Groundwater Sustainability Index (GWSI), Surface Water Sustainability Index (SWSI) and Atmosphere Sustainability Index (ASI)) were calculated for the specific case of study area considering the condition of sustainability of each pollutant based on the threshold limit values determined by the existing standards. Permissible minimum level of the ESI for UCG and CO_2 storage was also determined.

3.3.1 Subsidence sustainability index (SSI)

Considering the particular depth of the study areas the SSI value is illustrated for different scenarios of cavity diameter (Fig. 18). The results show that Subsidence Sustainability Index varies from 0.986 to 0.997 (the SSI is practically equivalent to 1), which means that subsidence in the study area will be negligible according to the proposed minimum permissible level of the ESI for UCG and CO_2 storage (Table 9).

Table 9 Proposals of ESI $_{UCG}$ and ESI_{CO2} for sustainability conditions

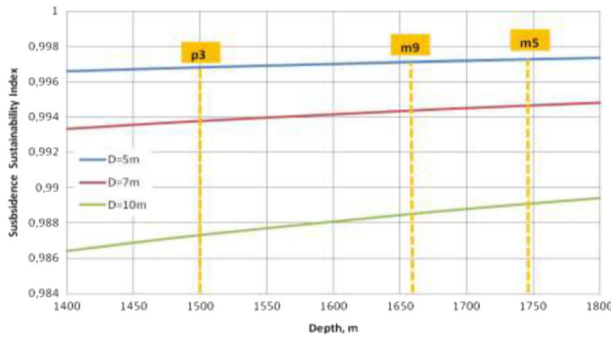| Sustainability level	Colour	Condition based in ESI$_{UCG}$
Very good		$ESI_{UCG} = 1.00$
Good		$0.75 < ESI_{UCG} \leq 1.00$
Moderate		$0.50 < ESI_{UCG} \leq 0.75$
Low		$0.25 < ESI_{UCG} \leq 0.50$
Very low		$0.0 < ESI_{UCG} \leq 0.25$

Fig. 18 Scenarios of Subsidence Sustainability Index in the study area for three selected coal seams and for different cavity diameters (5 m, 7 m and 10 m). Note: p3, m9 and m5 are designated coal seams within the same site

3.3.2 Groundwater sustainability index (GWSI)

The Groundwater Sustainability Index for the study area is simulated based on six typical environmental indicators in UCG processes ($n=6$): Sulphates (SO_4), Ammonia (NH_3), Phenols (C_6H_5OH), Polyciclic Aromatic Hydrocarbons (P.A.H.), pH and Calcium (Ca_{2+}), and using the groundwater quality standard as per the Bulgarian Regulation Nº1 of 10 October 2007 on the Exploration. The index was calculated for two cases: (a) for pH values <6.5 and unsustainable pH=0, and (b) for pH>9.5 and unsustainable pH=14. The results from simulations of GWSI behaviour illustrate the great variability and sensitivity of diverse pollutants of groundwater. So, it is important to apply preventive measures in the study area because of the aquifers in it.

3.3.3 Surface water sustainability index (SWSI)

While there is no significant presence of rivers on the surface of the study area, appropriate preventive measures should be used mainly because of the recharge areas of the aquifers. The sustainability index of surface water is assumed to be very good (with mean values near 1).
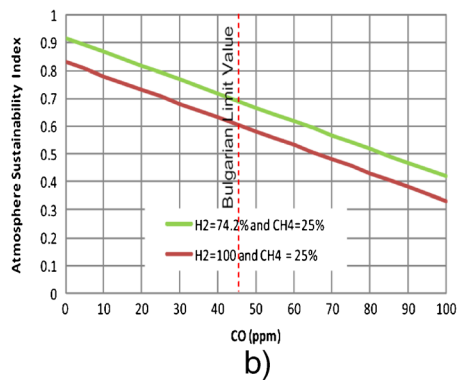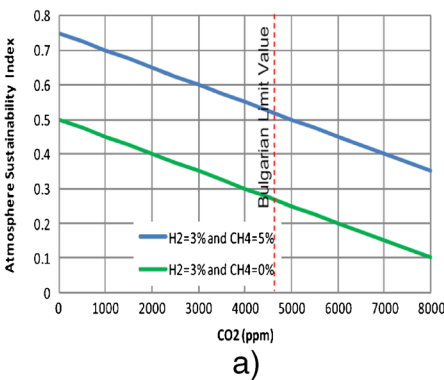

Fig. 19 **a** ASI behaviour for CO2, H2=3 %, CH4=0 and CH4=5 %, when CO=25 ppm; **b** ASI behaviour for CO, CH4=25 %, H2=74.2 % and H2=100 %, when CO2=1000 ppm

3.3.4 Atmosphere sustainability index (ASI)

The ASI simulation for a hypothetic UCG study area is based on four environmental indicators ($r=4$), using average values of Atmospheric Quality Standards. The ASI is calculated for two cases: (a) for $H_2<4$ % and $CH_4<5$ % and unsustainable $H_2=0$ and $CH_4=0$, and (b) for $H_2>74.2$ % and $CH_4>14$ % and unsustainable $H_2=100$ and $CH_4=100$. The simulation results for ASI behaviour for CO_2 gas variation of 0 to 8000 ppm, for $H_2=3$ %, $CH_4=0$ and $CH_4=4$, $CO=25$ ppm are shown in Fig. 19a. The simulation results for ASI behaviour for CO gas variation of 0 to 100 ppm, for $CH_4=25$ %, $H_2=74.2$ % and $H_2=100$ % and $CO_2=1000$ ppm are shown in Fig. 19b.

Applying the ESI model to the selected sites show that the subsidence in the study area will be negligible, the Groundwater Sustainability Index is expected to be high, the Surface Water Sustainability Index should be very good (due to the absence of surface waters in the area) and the Atmosphere Sustainability Index behaviour with several environmental pollutants shows a high ASI sensitivity with CO_2 concentration increment when compared to the CO emission.

These results show that the mathematical model developed for ESI has an excellent applicability for quantitative sustainability assessment of the UCG and CO_2 storage process. But in order to improve the quality of such an evaluation there is a need to introduce additional information not only from bibliographic sources but also field data that should be gathered in accordance with the requirements of the sustainability analysis.

4 Economic assessment

For the economic assessment of the UCG-CO_2 process, the basis of the developed model used for evaluation is a 308 MW combined cycle gas plant operating on UCG syngas, in which the CO_2 is separated, compressed and stored at or near the UCG process (Fig. 20).

The process taking place at each stage is modelled for flow, pressure and power requirements. Surface plant cost for CAPEX and OPEX and performance data are obtained from the literature by considering similar processes. The UCG process assumes CRIP technology. Bulgarian drilling costs were used to assess the underground construction costs. The individual
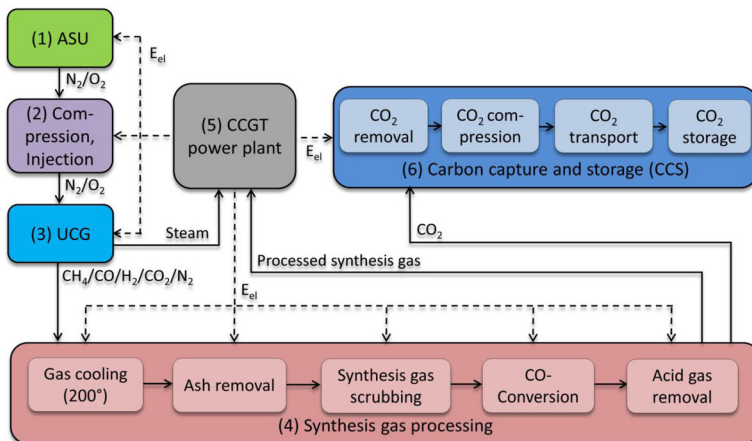

Fig. 20 Coupled UCG-CCGT-CCS process (Nakaten et al. 2013a)

Table 10 Geological input data considered by the commercial-scale scenario

Coal seam	Seam 1	Seam 2	Seam 3	Seam 4
Seam depth (m)	1,800	1,322	1,617	1,411
Seam latitude (km^2)	1.14	1.14	0.62	0.62
Seam thickness (m)	3.96	11	6.6	12
Available coal resources (million tonne)	8.37	23.25	7.59	13.79
Coal yield per gasification reactor (t)	58,083	439,255	116,617	385,511
Amount of gasification channels	25	24	30	16
Coal calorific value (MJ/kg coal)	33.16	33.84	35.58	33.84

component and fuel costs such as land acquisition, fees (*e.g.* concession fee for extraction), piping-, measuring-, control equipment, drilling, synthesis gas processing as well as oxidiser compression and injection, were brought together in a calculation which takes into account the levelised costs of electricity (COE) and CCS costs (Nakaten et al. 2013a). It is assumed that the coal, because of the depth, has no intrinsic value and royalties payment will not be required.

Taking into account the thermal regime in the study area calculations show a pressure loss of about 4.2 bar considering a well-head pressure (WHP) of about 15.8×10^3 kPa during the oxidiser injection and of 3.6 bar considering the UCG operation at slightly sub-hydrostatic pressure in the target coal seam, which is expected to be in an acceptable range for the chosen liner diameters and well dimensions. In the present study, it was decided to apply inner liner diameters of about 8.9 cm (3 ½ ") and about 12.1 cm (4 ¾ ") for the injection and production wells, respectively. The geological input data for the commercial-scale calculation are shown in Table 10.

Once the first gasification reactor is depleted, the maximum capture rate from the synthesis gas stream by post-combustion capture will be established according to the available storage capacity of the former UCG reactors (12.6 million m^3) used for CO_2 storage (cf. Paragraph 2.1.2, *Modelling of the geomechanical and thermal effect of the UCG and CO_2 storage processes*). This refers to 20.5 % of the produced CO_2, resulting in a remaining CO_2 amount of 79.5 %. As the investigation of alternative storage options for the remaining 79.5 % of CO_2 is not within the scope of the UCG-CCS project, this amount is released into the atmosphere applying a fix emission charge of 25 €/t CO_2. Table 11 presents the final economical modelling

Table 11 COE and CCS costs in the commercial-scale scenario (Nakaten et al. 2013a)

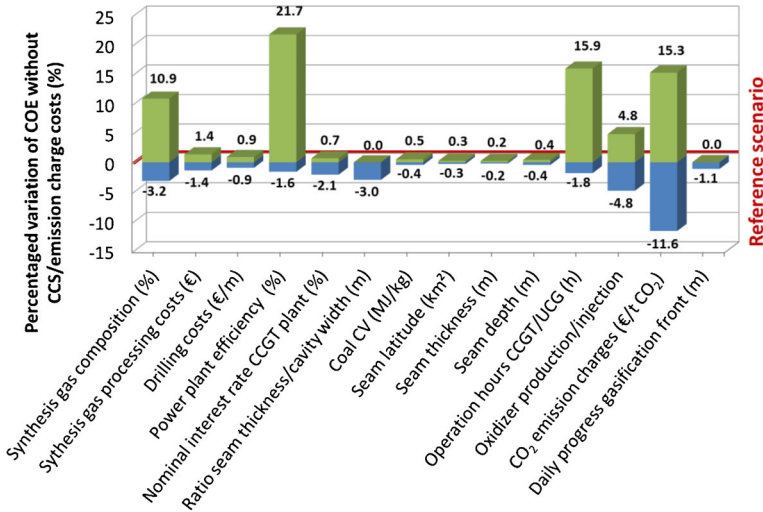| Target areas	
Total drilling costs (mio. €)	235.5
Share of drilling costs to total UCG costs (%)	11
Total coal yield for seams 2, 3 and 4 (%)	45.4
Number of gasification channels (–)	95
Injection wells (–)	8
Production wells (–)	4
Surface pipeline infrastructure (mio. €)	0.15
COE (€/MWh)	53.46
CO_2 emission charge (€/MWh)	23.11
COE+100 % emission charge (€/MWh)	78.55
COE+20.5 % CCS +79.5 % emission charge (€/MWh)	76.57

Fig. 21 Percentaged impact of all investigated parameters on COE without CCS/emission storage costs (Nakaten et al. 2013b)

results undertaken in the context of the study. COE for the coupled UCG-CCGT-CCS process are about 77 €/MWh for the combined utilisation of the study area coal blocks.

Sensitivity analysis and cost comparison of the UCG–CCS process with other methods of CO_2 sequestration was also undertaken. To assess the impact of uncertainties, a sensitivity analysis on the impact of 14 parameters on the overall COE of the coupled UCG-CCGT-CCS system was made by the implementation of different modelling scenarios.

The tornado diagram plotted in Fig. 21 summarises the influence of all investigated parameters on COE on a percentage basis. The results show that geological input parameters have a relatively low influence on COE with a maximum of about 3 % in the case of the cavity width to seam thickness ratio. However, technical implementation of the CCGT power plant (example, operating hours and plant efficiency) may increase COE by up to about 22 %, synthesis gas composition accounts for up to 11 % and oxidiser production accounts for up to 5 %. One reason why the current study geological parameters has a lower influence on COE than technical parameters is that the variation bandwidth was chosen to be narrow (±8 % and 10 % against ±25 % for the other cases), otherwise coal resources in the worst-case scenario would be insufficient to provide the daily required fuel for the CCGT plant. The main reason for the low sensitivity of geological parameters on COE is the minor influence of drilling costs (11 %) on the overall fuel production costs (5.6 €/GJ) outweighed by the high share of oxidiser production (58 %) and synthesis gas processing costs (16 %) (Nakaten et al. 2013b).

5 Conclusion and exploitation of results

3D geological and tectonic models of the study area have been constructed as a key part of assessing the feasibility of UCG-CCS in deep coal deposits. Suitable sites were identified by matching geological criteria for UCG site selection against available geology. Information from the geological and tectonic models was essential for the development and parameterisation of state-of-art models including geo-mechanical and cavity, hydro-geological,

environmental and techno-economic models. The study area has a complicated tectonic structure. Major faults (of Triassic age) have been identified around the target area, and while these can be avoided, little is known about any minor faults that exist in the Horsts between them.

The identification of suitable sites for UCG was based on a correlation between the geological features, physical parameters and techno-economic aspects of the studied areas. The suitability of coal seams was made on the basis of a set of quantitative and qualitative criteria that may be used and applied to other deposits with similar geological conditions. Part of these criteria refer to geometry and quality of the coal seams and are treated by the 3D geological model. Another part considers the tectonic structure of the deposit, hydrogeological features, and parameters pertaining to geomechanical, engineering and environmental issues. The preliminary selected sites that mostly satisfied the UCG-site selection criteria and had the best potential for UCG and subsequent CO_2 storage were bounded by faults. The selected coal seams pertaining to them were between 1,100m and 1,500m deep, amounting in total to over 75 Mt of UCG compliant coal.

A set of thermal-mechanical coupled models have been developed for the prediction of UCG cavity growth, surface subsidence as well as geologic faults reaction. These models can be employed in future feasibility studies and risk assessments of UCG-CCS projects, given that the lithological information and material properties of the rock and coal from the specific coal sites are available. A safety distance of at least 150m between the gasification channels and the geologic faults has been proposed to avoid any potential fault reactivation and consequent leakage of UCG gases, contaminants or CO_2. Even though each assessment of a prospective UCG-CCS area has to be site-specific, the presented results can be used as guidance for future UCG feasibility studies. Also, a set of UCG-CCS site selection criteria is prescribed, which can be taken into account for future UCG site design and risk assessment demanded by the mining and environmental authorities.

The hydro-geological environment was also simulated to characterise the pre and post gasification conditions, as well as conditions during the stages of UCG. Regional scale and local scale hydro-geological models were developed, whereas the latter were applied to assess the temporal and spatial changes during the different stages of the UCG-CCS process. The models were also used to assess environmental risks related to transport of UCG contaminants. The analyses show that the UCG-CCS activities at the study area would not have a significant impact on the groundwater quality considering the given assumptions. Thus, It is not to be expected that given regulations on water quality will be compromised related to the water quality of the MalmValanginian aquifer located above the study area and representing the most relevant source of freshwater in the region.

Drilling and completion technologies are generally available and can be readily applied for dual use wells required for UCG and CO_2 injection. A combination of conventional and coiled tube drilling is proposed. The conventional methods should be used to drill the vertical/caprock sections, while coiled tubing is suggested for the build-up and horizontal/in-seams sections. It is recommended that the UCG injection wells, rather than the production wells, be used for CO_2 injection due to potential corrosion in UCG production wells resulting from high temperatures and the composition of the UCG synthesis gas before processing at the surface.

As part of the environmental assessment, a mathematical model was developed and sensitivity analyses of Environmental Sustainability Index (ESI) conducted. The mathematical model used to establish the ESI for the processes of UCG and CCS. Its application to the study area indicates negligible subsidence as supported by geomechanical modelling, no significant impacts on freshwater bearing aquifers and a contribution to greenhouse gas emission mitigation, if UCG is combined with CO_2 storage. The economic benefit of combining CCS with

UCG was assessed. In addition to sensitivity analyses, a cost comparison of the UCG-CCS process with alternative methods of CO_2 storage was carried out. Preliminary studies indicate that UCG-CCS is economic as emission charges exceed 15 €/t CO_2. Geological parameters have a great effect on drilling costs; however, their effect on the overall cost of electricity (COE) is relatively low in comparison to the technical model-input parameters.

The feasibility study indicates that it is technically possible to conduct UCG-CCS operations in the selected sites without significant environmental impacts. It is also economically viable, especially if the charge for CO_2 emission is considered. While it may technical achievable to embark on UCG projects, their viability depends strongly on set guidelines that border on general and site-specific threshold conditions. Moreover, the incorporation of CCS improves the economies of the operation since external storage requirements are no longer essential. These guidelines and standards as determined herein can be adopted either directly or indirectly during establishment of policies and the deployment of strategies to combat global climate change.

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